

Workshop Critical Review:
Assessing Atmospheric Deposition of Mercury
to Western Water Bodies

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Abstract

There are major challenges in dealing with mercury pollution. Harmful concentrations of mercury in fish in a particular water body can come from multiple, diverse sources. In order to adequately reduce mercury concentrations in fish in a particular water body, the relative importance of the different mercury sources (i.e., other water bodies, land, direct discharges, and air deposition) needs to be established. When mercury deposition from the air is a major determinant of contamination in a particular water body, then the relative importance of local, regional and even global sources of mercury becomes an important consideration.

Establishing an exit strategy for better assessing and dealing with mercury air deposition as a source of contamination for Western water bodies is the main goal of the workshop. As a starting point for the workshop discussions, this review summarizes:

- what is known about mercury, particularly in the western U.S.,
- assessments of mercury air deposition and their relevance to the western U.S.,
- approach taken in Colorado TMDL as a case study,
- findings from other TMDLs, and
- mercury air quality policy and implementation issues in the West.

Each section concludes with an overview of findings and implications for assessing mercury air deposition to western water bodies. These conclusions, outlined below, highlight key concerns addressed in the development of the workshop exit strategy.

What is known about mercury, particularly in the Western U.S.

Overall, there are uncertainties at each part of the mercury cycle (i.e., sources, atmospheric transport and transformation, deposition, water chemistry, food chain, and

human health impacts). All of these need to be taken into account when assessing the role of mercury air deposition to contaminated water bodies.

Emissions. In general, the largest uncertainties with respect to anthropogenic sources of mercury that may be affecting a particular water body are associated with the relative breakdown of elemental vs. oxidized vs. particulate mercury coming from different sources. For the Western U.S. in particular, forest fires also may be an important but as yet not well quantified source of mercury. The potential contribution from abandoned or operating mercury mines in the West also may be significant for water bodies in the vicinities of the mines. By far, the largest uncertainties are associated with estimates of natural sources, re-entrained mercury and man-made emissions from other countries outside North America and Europe.

Air Chemistry. The atmospheric lifetime of mercury strongly depends on the transformation processes. Key uncertainties include the completeness of the assumed aqueous phase mercury conversion processes and the amount of mercury gas that can adsorb onto particles. The temperature dependence of most atmospheric reactions also is yet to be established. The conversion processes depend on concentrations of other important air pollutants, such as ozone, whose concentration patterns are known with varying degrees of confidence in different areas of the West, the U.S. as a whole, and the world.

Deposition. In general, the mercury deposition data gaps in the western U.S. are quite large. There are fewer monitoring sites for wet deposition in the West than in the East. For dry deposition of mercury, there is no real national effort in place. Since dry deposition can be equivalent to wet deposition, particularly in the dry climates of the Western U.S., this is a particularly important data gap. In addition, monitoring generally does not provide information on the particular species of mercury being deposited. This is also a particularly important limitation since the chemical form of mercury determines how effective it is in causing a health risk. Snow pack observations can be used to help

supplement these sparse monitoring data and ice cores provide long term information on deposition trends.

Measurements. Comprehensive, speciated mercury measurements of atmospheric mercury at the emissions sources, in the air and at deposition sites are still in developmental stages. This lack of detailed data on the different forms of mercury adds to the challenge of understanding the fate and transport of mercury.

Health Risks. The ability of deposited mercury to form methyl mercury in water determines the level of harm associated with the deposited mercury since different forms of mercury react at different rates to form methyl mercury in water. The health impacts of mercury also are linked to other atmospheric pollutants. For example, increasing the acidity and/or the dissolved organic carbon levels enhances the mobility of mercury in the water, thus making it more likely to enter the food chain. Acid deposition comes from emissions of sulfur and nitrogen oxides. Combusted fossil fuels are major sources of these chemicals, including mercury. Better understanding of these relationships is important to identifying co-benefits of different multi-pollutant reduction strategies. In addition, given the ongoing concerns about health risks that may occur at even lower exposures, even lower emission reductions may be needed to protect health. The implications of these uncertainties regarding exposure also need to be considered.

Fish Advisories. Fish advisories are a main indicator of the actual risk of mercury to the population. The existence of fish advisories for the West indicate that mercury is definitely a health issue in many western states. Additional data are needed on the exposure levels at which people experience subtle, but persistent, adverse neurological effects. The current EPA reference dose for chronic toxicity may not be adequate for protecting against these effects, suggesting that more conservative protective actions may be needed.

Mercury Assessments and their Relevance to the Western U.S.

Several recent comprehensive air quality modeling studies provide useful indications about the relative importance of different sources (i.e., from global to local) to deposition at a particular water body or area. However, because of the uncertainties in characterization of sources, chemical transport and transformation, and deposition processes, there are considerable uncertainties in the model results themselves. These uncertainties must be taken into account when using the modeling tools to estimate actual load reductions from different sources that may be needed to protect particular waters.

In general, the studies indicate that air deposition can come from sources beyond the watershed, state or even continental U.S. The extent of contributions from such distant sources needs to be considered particularly when there are no obvious nearby sources that could clearly be accountable for the mercury deposition leading to health risks.

TMDLs for Colorado and Other States and Regions

TMDLs, as the main mechanism for establishing necessary reductions to achieve water standards, are difficult to conduct for water bodies that are subject to significant air deposition. Determining the relative contributions of different mercury air emission sources remains a large challenge for western states that are beginning to evaluate the importance of air deposition to contaminated water bodies. The Colorado case study illustrates a number of outstanding challenges in assessing air deposition and assigning necessary source reduction levels.

As illustrated by mercury TMDL efforts in other parts of the country, regional approaches may be needed to achieve needed water protection goals. This is the case for water bodies where air deposition is a major contributor and where the main sources of the air deposition are likely to be beyond state boundaries.

Mercury Reduction Strategies

Mercury reduction strategies are being developed at all levels of government. Particular attention is being given to coal-fired power plants which are an unregulated, important source of mercury as well as other air pollutants. Multi-pollutant controls are being investigated as promising approaches to dealing with mercury and other related pollutants simultaneously. These considerations are important for the West where coal-fired power are a major source of airborne mercury and where additional controls could result in reductions in other pollutants as well as mercury.

In terms of establishing policy strategies that will better guarantee protection of water bodies throughout the U.S., broader scale policies may be needed. For water bodies that are affected by mercury air deposition that originated from multiple, diverse and sometimes distant sources, reductions from distant sources may need to be part of the control strategy.

Many technical assessment and policy challenges remain. Continued and even closer collaboration of air and water scientists and policy analysts will be needed. Given the global nature of mercury source-receptor relationships, international collaboration also will be needed to insure that the necessary long-term reductions in harmful levels of mercury will be possible in the U.S. and around the world.

Workshop Exit Strategy

The overarching question facing the workshop in particular and the mercury assessment and policy communities in general concerns determining and dealing with mercury air emission sources that contaminate specific water bodies. To begin to better address these science and policy challenges the workshop exit strategy focuses on recommendations on how to:

- improve understanding of mercury in the West,
- conduct assessments to identify important sources and reductions needed,

- complete next phase of Colorado's TMDL,
- address other western TMDLs, and
- determine how mercury air policies can best protect Western water bodies.

Each section of the review ends with a summary of findings and specific discussion topics for guiding the development of the exit strategy.

The document concludes with a summary of exit strategy recommendations developed at the end of the workshop by the participants. These will server as the starting point for the development of a comprehensive exit strategy.

Introduction

Mercury is a growing concern worldwide. In the U.S. mercury makes more surface waters impaired for fishing than any other toxic contaminant. Fish consumption is most often the route of human exposure to mercury. As a result, the U.S. Food and Drug Administration routinely issues fish consumption guidelines. Currently, most states have mercury fish advisories. These are issued when mercury concentrations in fish are unsafe. Other countries around the world, including Canada and several European countries, also issue fish consumption warnings due to elevated levels of mercury in fish. The form of mercury found in fish, methylmercury, is a neurotoxin that causes brain and nervous system damage. Those most at risk from methylmercury are children and unborn babies of mothers who eat mercury contaminated fish during pregnancy.

There are major challenges in dealing with mercury pollution. Harmful concentrations of mercury in fish in a particular water body can come from multiple, diverse sources. In order to adequately reduce mercury concentrations in fish in a particular water body, the relative importance of the different mercury sources (i.e., other water bodies, land, direct discharges, and air deposition) needs to be established. When mercury deposition from the air is a major determinant of contamination in a particular water body, then the relative importance of local, regional and even global sources of mercury becomes an important consideration.

Assessing the relative importance of different sources of contamination requires characterization of emissions and impacts and the multiple processes that translate mercury emissions into human health risks. It also involves establishing the levels of uncertainty associated with the data and models used for the assessment. The challenges of establishing these relationships and using these assessments to better inform policy makers are central to the workshop discussions. Through the workshop process,

strategies for dealing with mercury contamination issues in the Western U.S. are explored and developed.

The critical review sets the stage for the workshop deliberations by summarizing:

- relationships among mercury emissions, deposition and harmful levels of mercury in fish, particularly in the West,
- assessments of mercury air deposition throughout the U.S.,
- Western TMDLs and research related to the mercury issue, and
- mercury reduction strategies developed across the country.

The section on understanding mercury in the West discusses:

- Cycles: air deposition and how it relates to other pathways.
- Air emissions: anthropogenic, natural, other (e.g., forest fires).
- Transport and chemistry: relative rates and role of other chemicals.
- Deposition: wet and dry deposition monitoring, snowpack, ice cores
- Mercury measurements: need for and status of speciated, continuous.
- Impacts: lake chemistry, food chain and health impacts.
- Fish advisories: indicators of risk.

The next section on assessments of mercury deposition summarizes:

- Mercury Maps: relating mercury emissions to mercury in fish tissue.
- Assessment findings: results from several key mercury assessments.
- Modeling tools: comparison of analysis approaches.

The TMDL section reviews:

- TMDL process and the criteria for identifying water bodies at risk
- Current Colorado TMDLs as a case study.
- Other Western TMDLs and mercury air deposition studies.
- Regional approaches to TMDLs (e.g., the northeastern U.S. activity).

The mercury reduction strategies section outlines:

- Air quality policies and strategies: federal, state, regional.
- Mercury control options: coal-fired power plants and other sources.

The review concludes by presenting a list of topics addressed at the end of the workshop and a summary of recommendations developed by the participants. These provide a framework for developing a more comprehensive workshop exit strategy.

Understanding Mercury in the West

Mercury is a chemical element and like all chemical elements, it can neither be created nor destroyed. The pathways leading to harmful chemical compound forms of mercury are complex and interconnected. The relative importance of the different pathways varies from place to place, making definitive assessments of source contributions to adverse impacts of mercury for a particular area often very challenging. This section outlines the global mercury cycle in general and then examines each stage in more detail. Key uncertainties and implications for addressing mercury in the western U.S. are highlighted.

Global Cycle

The mercury cycle, schematically illustrated in Figure 1, provides a framework for outlining pathways to harmful forms of mercury. Mercury is emitted into the air from anthropogenic (e.g. fossil fuel combustion) and natural (e.g., volcanic eruptions) emission processes and from re-entrainment. Re-entrained mercury originally came from both anthropogenic and natural emissions. Mercury is emitted as elemental, oxidized or particulate mercury. (e.g., EPA, 1997).

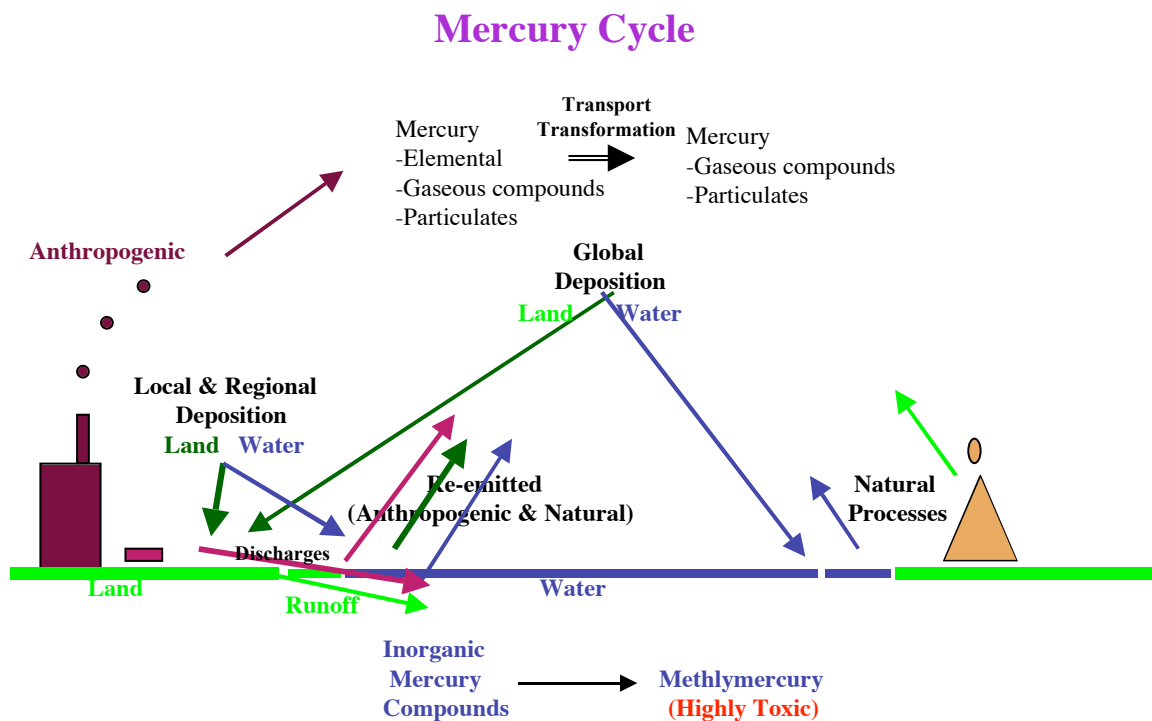


Figure 1. General Air-Land-Water Mercury Cycle

Once airborne, mercury in its different forms can chemically react and can be transported. Elemental mercury is not very reactive and can travel great distances. Eventually mercury is deposited, through wet or dry processes, into the oceans, land surfaces or in-land water bodies.

Mercury deposited into the in-land water bodies is of greatest concern to human health. This deposited mercury can undergo aqueous phase chemical reactions to form the harmful methylmercury. The toxic methylmercury can then be accumulated up the food chain. People eating contaminated fish are at risk.

Global Cycle. Overall, as is pointed out in the remainder of this section on mercury science, there are uncertainties in each part of the mercury cycle. These must be considered when assessing quantitative links between particular sources and impacts. Strategies for taking these uncertainties into account will be an important part of the workshop exit strategy discussions.

Air Emissions

Mercury in the atmosphere is mainly the byproduct of direct human activities (e.g., combustion of coal) and natural processes (e.g., volcanic eruptions). Mercury can also be re-emitted to the atmosphere by biologic and geologic processes. These draw on a pool of mercury that was deposited to the earth's surface after initial mobilization by either anthropogenic or natural activities.

There are considerable uncertainties regarding the levels of natural and re-emitted mercury into the atmosphere. It has been estimated that roughly 2/3 of the global emissions may come from re-emitted and natural sources (approximately 1/3 each). Re-emitted mercury could have originated from natural or anthropogenic sources. About 6% of the anthropogenic emissions come from the U.S. The breakdown with respect to anthropogenic sources, however, has begun to be inventoried with more confidence, particularly in North America and Europe (e.g., Pacyna and Pacyna, 2002; EERC. 2003, GEIA). An estimate of all mercury sources for the U.S. is illustrated in Figure 2.

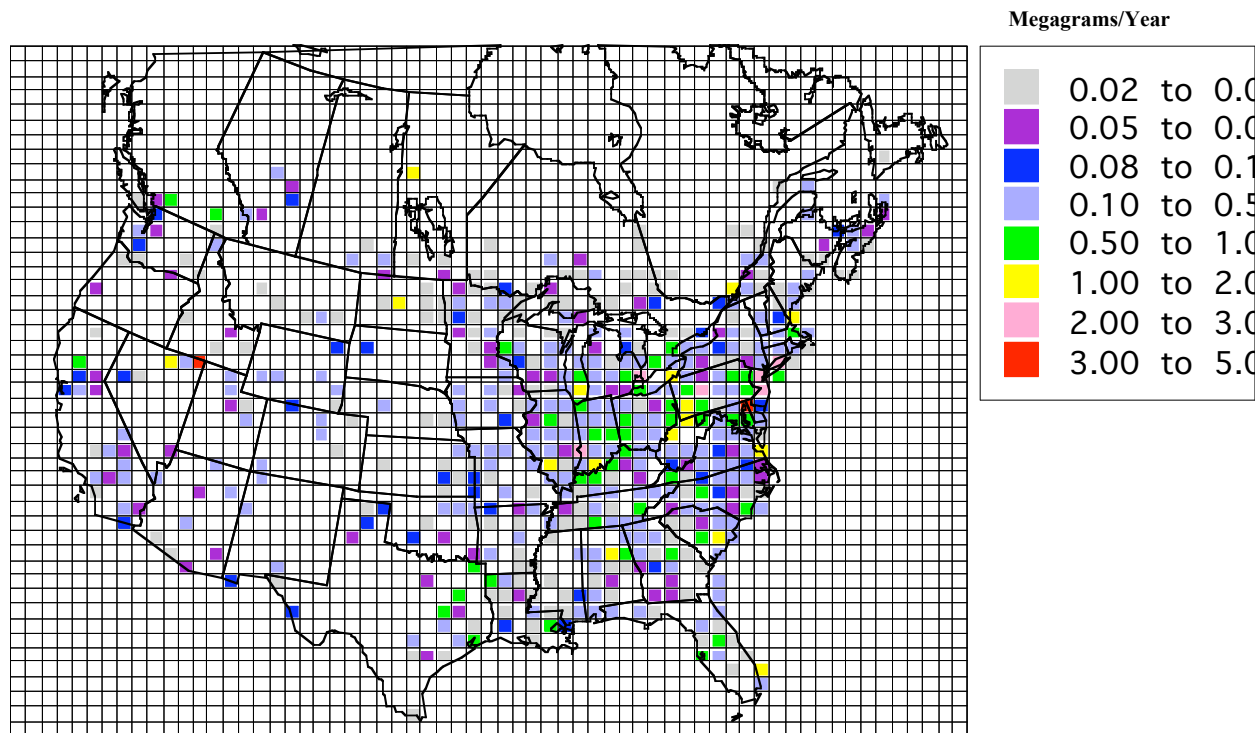


Figure 2. Total annual emissions from all mercury sources.. Units: Megagrams/year. (Seigneur et al, 2001)

Anthropogenic Sources

Mining of mercury and a host of commercial, industrial and medicinal uses for mercury go back at least to Roman times. The mined mercury is usually found in the geosphere as the mineral cinnabar, HgS . Mercury mining in the U.S. mainly takes place in the California coastal ranges. Alaska also has many mercury deposits. Overall, mining represents a small source of mercury.

Mercury has been used extensively in the extraction of gold. During the gold rush period, mining was a major source of mercury (e.g., Schuster et al, 2002; USGS, 2002). Mining and abandoned mines could be a significant source of mercury to nearby waters (e.g., USGS Mercury Mines).

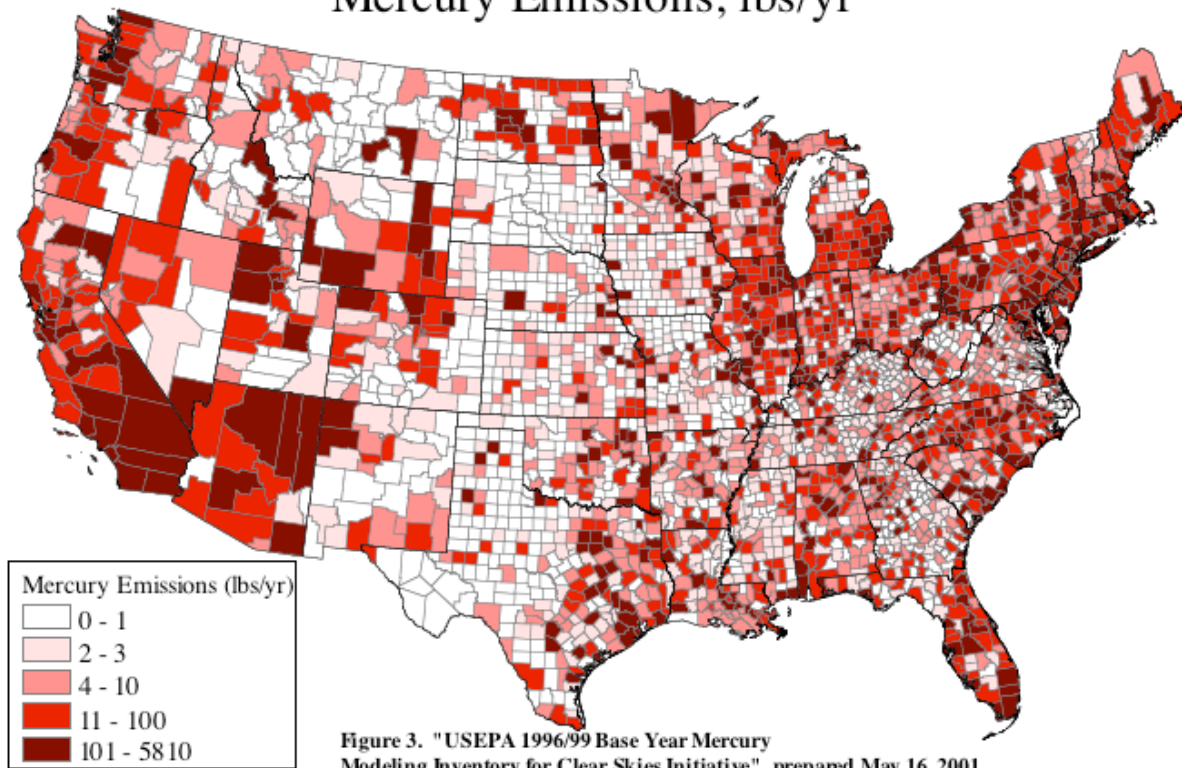
Today, mercury is used in fluorescent lamps, wiring devices/switches (thermostats), mercuric oxide batteries, instruments that measure pressure and temperature, and in dental tools. Mercury is used as a chemical in the production of chlorine and caustic soda (by mercury cell chlor-alkali plants), metal amalgamation, nuclear reactors, wood processing; as a solvent for reactive and precious metals; as a catalyst for chemical reactions; and as a preservative in various pharmaceutical products. Most of these uses (apart from the production of chlorine by mercury cell chlor-alkali plants) are not significant sources of mercury emissions into the air (EPA, 1997).

As described in EPA's Mercury Report to Congress (EPA, 1997), 80% of the total anthropogenic emissions can be attributed to four specific source categories, with coal-fired utility boilers being the largest. Municipal waste combustors, medical waste incinerators and hazardous waste incineration are the next largest.

There appears to have been a trend toward decreasing total mercury emissions from 1990 to 1995. This was mainly due to a 50% decline in emissions from municipal waste combustors and 75% from medical waste incinerators since 1990. Emissions from these sources have declined due to plant closures and reduction in the mercury content of the waste stream. They are likely to continue to decline further due to regulatory action of the U.S. EPA. More recent preliminary estimates of the mercury emissions in the National Toxics Inventory (NTI) for the U.S. in 1999 indicate that the relative importance of coal utility boilers to the overall total emissions has increased (EPA—NTI).

The total mercury emission patterns for the U.S. are determined mainly by location and magnitude of the utility and other dominant point source emitters. Mercury emissions are higher in the eastern U.S. than in the West, as expected, since utility emissions are much higher in the eastern U.S. (EPA, 1997). These utility-determined patterns are even more pronounced for the 1999 emissions (EPA—NTI).

Mercury Emissions, lbs/yr



In order to better understand the relationship between sources of mercury and impacts, it is important to characterize the speciation of the mercury being emitted from different sources. Coal fired utility boilers, municipal waste combustion, commercial/industrial boilers and medical waste incinerators all are associated with high temperature processes. Mercury has a relatively low boiling point and is therefore volatilized during high temperature combustion operations and is emitted into the atmosphere as elemental mercury vapor or gaseous and particulate mercury compounds.

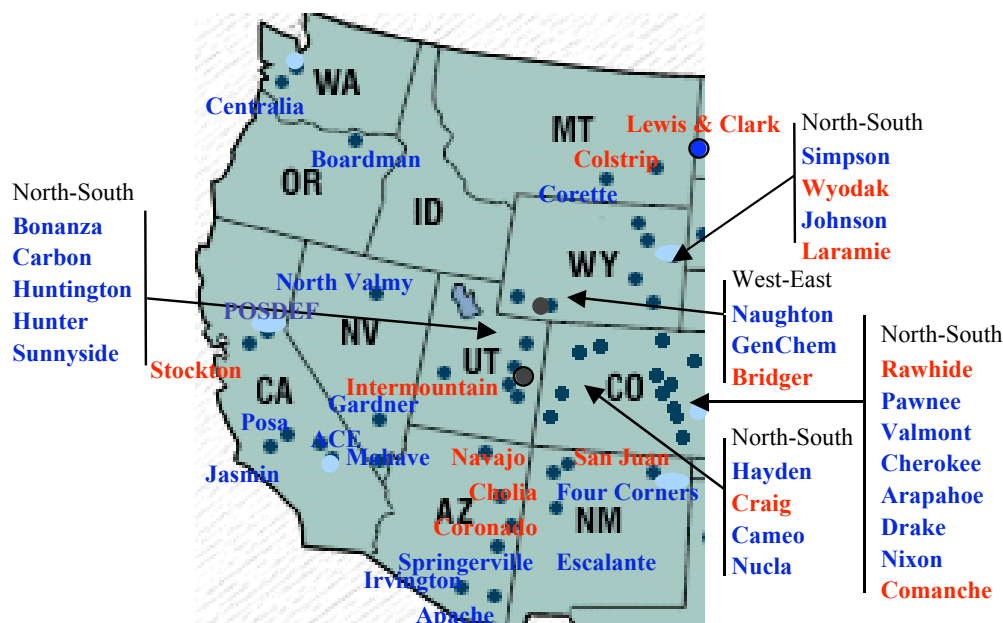
Results from the recent national Information Collection Request (ICR) program which provides a detailed assessment of mercury emissions from coal fired utilities indicates that 48 tons of mercury were emitted from coal-fired units in 1999 and that, on the average, the speciation of emitted mercury was about 3% particulate, 43% oxidized gaseous (i.e., ionic) and 54% elemental mercury. This breakdown varies from plant to

plant depending on the coal being burned and the emission controls that are in place. (EPA—ICR).

The breakdown for other sources also varies. For example the speciation for municipal waste combustors is estimated to be 20% particulate, 58% ionic, and 22% elemental. For medical waste incinerators, the breakdown is estimated as 20%/75%/5%. (EPA—NTI).

Based on the 1999 ICR emission analysis (EPA--ICR), of the western states (i.e., Montana, Wyoming, Colorado, New Mexico, Idaho, Utah, Nevada, Arizona, Washington, Oregon and California), New Mexico has the highest emissions from coal-fired utilities with a state total of 1.09 tons and ranks 15th compared to all of the other states in the U.S. The other western state totals, in order, include: Wyoming - 0.914, Arizona – 0.627, Montana – 0.471, Washington – 0.265, Colorado – 0.255, Nevada – 0.165, Utah – 0.146, Oregon – 0.084, and California – 0.018. The specific plants contributing to these totals are listed in Figure 4. Plants that were included in the detailed ICR mercury speciation analysis are noted in red.

Figure 4. Western Coal-Fired Utilities
 (Facilities included in special ICR sampling noted in red.
 Others noted in blue.)



Natural Sources and Forest Fires

Natural sources include mainly gaseous emissions of mercury (i.e., mainly in its elemental form) from the oceans, natural deposits and volcanoes. Just as there are hot spots of anthropogenic mercury sources, natural mercury hot spots also exist. These are generally associated with mercury containing rocks, soils, and mercury-enriched geological features (e.g., Lindberg, 2002, GEIA).

Forest fires, which are both natural and human-caused, also are a source of mercury. Researchers are estimating that the overall contribution of mercury from biomass burning around the world could be as much as 25% of all anthropogenic sources. (NCAR, 2002). Since fires are a frequent occurrence in the western U.S., they may be a potentially large contributor at least during times of the year when fire danger is high.

Emissions. *In general, the largest uncertainties with respect to anthropogenic sources of mercury that may be affecting a particular location or water body are associated with the relative breakdown of elemental vs. oxidized vs. particulate mercury coming from a particular source. For the Western U.S. in particular, forest fires also may be an important but as yet not well quantified source of mercury. The potential contribution from abandoned or operating mercury mines also may be significant for nearby water bodies. By far, the largest uncertainties are associated with estimates of natural sources, re-entrainment and man-made emissions from other countries outside North America and Europe. The workshop exit strategy will need to address these uncertainties and potentially important sources that are unique to the West.*

Transport and Chemical Transformation

Mercury, present in the Earth's atmosphere, is in the form of elemental mercury vapor, reactive (i.e., oxidized) gaseous mercury and particulate mercury. When mercury, in these forms, is released into the air, it is transported, and sometimes chemically transformed, and then deposited back onto the earth's surface at various rates. The rates of transport and transformation depend on the chemical form of the emitted mercury, the height of the emissions and atmospheric conditions (e.g., wind speeds, precipitation). Elemental mercury emitted high above the ground can persist in the atmosphere up to a year or more and be transported around the world while the more reactive forms can be deposited to land and water much closer to the sources. Airborne mercury also can undergo chemical reactions that lead to mercury compounds that are more quickly deposited to the earth's surface (e.g., EPA, 1997).

Mercury transformation processes include gas-phase reactions, reactions in the aqueous phase (e.g., cloud droplets), gas/aerosol physical and chemical processes, and aerosol (i.e., particle) processes. The gas-phase reactions include the oxidation of elemental mercury to oxidized mercury by ozone, hydrogen chloride, hydrogen peroxide,

and molecular chlorine. The aqueous-phase chemistry includes the reduction of oxidized mercury to elemental mercury via reaction with hydroperoxy radicals and by the formation of the sulfite complexes as well as the oxidation of elemental mercury to oxidized mercury by dissolved ozone, hydroxyl radicals and chlorine. Gaseous oxidized mercury also can be adsorbed onto particulate matter (e.g., EPA Models; Ryaboshapko et al, 2002; Seigneur et al, 2002).

It is important to underscore the important roles other key atmospheric chemicals play in the mercury transformation processes. As noted, ozone, sulfur compounds and particulates are particularly important in mercury atmospheric chemistry. This means that emissions from several other important air pollutants directly affect mercury. These include emissions of nitrogen oxides and volatile organic compounds which form ozone as well as particulates, emissions of sulfur dioxides which contribute to particulate and other gaseous sulfur compounds, and direct emissions of particulate matter. All of these other chemicals are well-known for their own harmful impacts on human health and the environment.

Transport and Transformation. The atmospheric lifetime of mercury strongly depends on the transformation and transport processes. Key uncertainties include the completeness of the assumed aqueous phase mercury conversion processes and the amount of mercury gas that can adsorb onto particles. In addition, the temperature dependence of many reactions is not yet known. The conversion processes depend on concentrations of other important air pollutants that are known with varying degrees of confidence in different areas of the U.S. and the world. Because mercury chemistry and transport determine the extent to which particular sources can contribute to contamination nearby or at a distance, the workshop exit strategy will need to address how best to take into account these complex but important atmospheric processes.

Deposition

Airborne mercury reaches the land and water via wet and dry deposition processes. All three major forms of mercury can be dry deposited and the rates of deposition will vary depending on the deposition surface characteristics and meteorological conditions. Wet deposition rates depend on the cloud composition and precipitation patterns. Scavenging of mercury by falling precipitation varies considerably. Not much if any scavenging occurs for the elemental mercury while all of the oxidized form is likely to be scavenged. Probably around half of the particulate form of mercury is scavenged (e.g. Seigneur et al, 2002).

Deposition monitoring establishes trends in the amount of mercury being deposited in different regions of the country. Analysis of snowpack provides an indication of levels of mercury being deposited, particularly at higher elevations. Assessment of mercury levels in snowpack also provides an indication of mercury that is likely to reach nearby lakes as a result of snow pack thaw and resulting runoff. Analysis of ice cores provides an indication of long-term trends in mercury deposition. All of these data sources together help establish deposition patterns which can be used with emissions information and data on mercury in fish to begin to assess relationships between sources and impacts.

Wet and Dry Deposition Monitoring

The National Atmospheric Deposition Program (NADP) provides observations of mercury concentrations and wet deposition around the U.S. At this time there is no national effort focused on dry deposition. The NADP maps indicate that mercury levels in the west are similar to those in the east. In fact the highest concentration in rainfall for 2000 reported by the mercury network was in New Mexico. Wet deposition levels reported in the west also are comparable to those in the east with Colorado reporting the

highest for the western sites. There are many more observations for the eastern U.S. while some states in the west and Midwest do not have any sites. However, the general pattern for the areas that are represented shows that the West and East both have variable levels of mercury and are within the same ranges (NADP).

The annual average concentrations in rainfall and total annual wet deposition patterns shown in Figures 5a and 5b are based on NADP findings. The Western sites are:

- Buffalo pass, Routt County, Colorado,
- Caballo, Sierra County, New Mexico,
- Seattle, King County, Washington,
- San Jose, Santa Clara County, California, and
- Covelo, Mendocino County, California.

Mercury Concentrations 2000

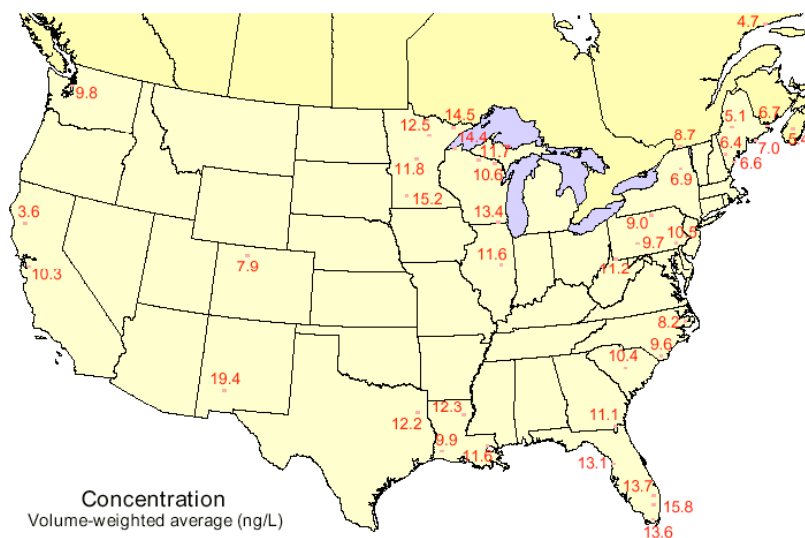


Figure 5a. Annual Average Mercury Concentrations in Rainfall for 2000

National Atmospheric Deposition Program, Mercury Deposition Network.

<http://nadp.sws.uiuc.edu/mdn/>

Mercury Deposition 2000

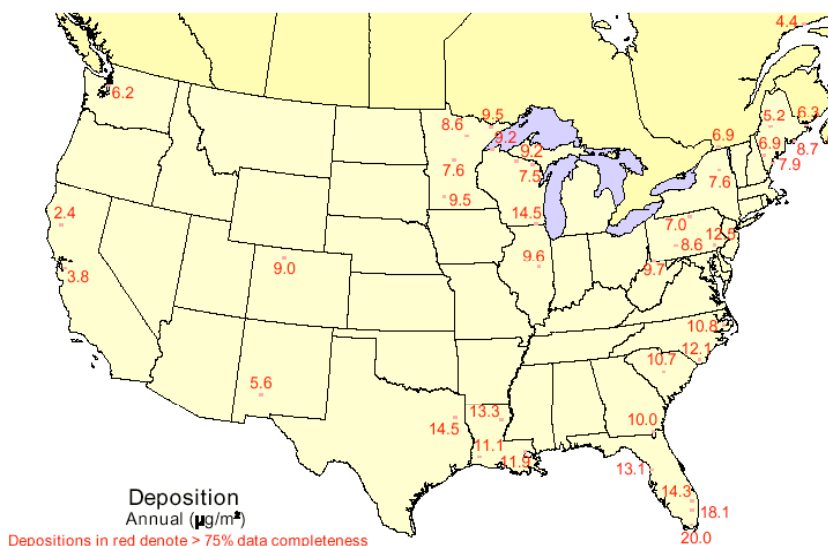


Figure 5b. Total Annual Mercury Wet Deposition for 2000
National Atmospheric Deposition Program, Mercury Deposition Network.
<http://nadp.sws.uiuc.edu/mdn/>

Snowpack Observations

Additional information on mercury deposition at high elevations is becoming available from special studies of mercury along with other chemicals in snowpack. Snowpack generally represents the entire mercury deposition via precipitation in these high altitude areas. By comparing mercury and the other chemicals in the snowpack with chemical emission information from key sources in the area, relationships between the deposition and the emission can be explored. Snowpacks at two high-elevation sampling sites near McPhee and Sanchez Reservoirs in southern Colorado have been selected for

study recently to establish a baseline that will be used to help establish levels of deposition in these areas and help determine sources of the deposition. Early findings suggest a connection between mercury deposition at these locations and emissions from near-by coal-fired power plants (Ingersoill, 2000).

Ice Cores

Ice cores provide a record of long term trends in mercury deposition. The unique core collected from the Upper Fremont Glaciers in Wyoming contains a high resolution record (1720-1993) of total atmospheric releases. This is a unique record for the U.S. The record indicates major atmospheric releases of both natural and anthropogenic mercury from regional and global sources. The record indicates major atmospheric releases from both natural and anthropogenic sources. Integrated over the past 270-year ice-core history, anthropogenic inputs contributed 52%, volcanic 6% and background 42%. During the past 100 years, anthropogenic inputs have contributed 70% of the total. These findings substantiate the fact that contributions from anthropogenic mercury sources have been increasing substantially in recent history (Schuster et al, 2002).

Deposition. The deposition data gaps in the western U.S. are quite large. There are many monitoring sites for wet deposition in the West than in the East. For dry deposition of mercury, there is no real national effort in place. Since dry deposition can be equivalent to wet deposition, particularly in the dry climates of the Western U.S., this is a particularly important data gap. In addition, monitoring generally does not provide information on the particular species of mercury being deposited. This is also a particularly important limitation since the form of mercury determines how effective it is in causing a health risk. Snowpack observations do help supplement these sparse deposition data and ice cores provide long term information on deposition trends. The workshop exit strategy will need to address how to best use the deposition data at hand and augment these data in order to establish an indication of deposition rates particularly at contaminated sites.

Mercury Measurements

In addition to the spatial sparseness of data on total mercury, particularly in the West, mercury data is also limited in temporal and chemical detail. Data on mercury in its various chemical forms (i.e., elemental, oxidized, particulate) and monitoring for short time periods (e.g., less than a day) also are lacking. Mercury data of this level of spatial, chemical and temporal detail is needed to help better understand the chemical cycles and develop most effective reduction strategies.

The ability to perform needed mercury measurements is still a challenge. Continuous or near-continuous mercury monitoring systems are showing promising advances in both analytical sensitivity and robustness. The Ontario Hydro wet-chemistry method, EPA Method 29 and EPA Method 101A for measuring total and speciated mercury provide good results with high sensitivity but have high costs and cannot provide real-time data.

Continuous mercury measurements of coal-derived flue gases are difficult because of the low concentrations of mercury and the high concentrations of fine particulates and acid gases which interfere with measurements. Pretreatment and conversion systems are necessary to provide standard samples for analysis.

Other techniques using filter collectors are being developed. For example, the Electric Power Research Institute (EPRI) carbon collection system is promising. Although it is not continuous and it requires some manual input, the technique is relatively simple and low cost and has demonstrated high precision and sensitivity.

Accurately measuring all forms of mercury simultaneously is very important for understanding the behavior of mercury in the environment. Temporal and spatial monitoring of mercury species concentrations and deposition can be very revealing. For example, recent measurements of atmospheric mercury were taken at a rural site in

Georgia to compare expected and observed mercury speciation results. Observed total mercury agreed with estimates based on modeling emissions. However, the speciation results differed by at least 50% (EEEC, 2003). Fortunately instrumentation for the simultaneous measurement of all three forms of mercury is now commercially available (Friedli, 2003)., making more of these necessary detailed analyses possible.

Measurements. Comprehensive, speciated mercury measurements of atmospheric mercury at the emissions sources, in the air and at deposition sites are still in developmental stages. This lack of detailed data adds to the challenge of understanding the fate and transport of mercury. Review of availability of more detailed measurement techniques for enhancing studies of air deposition to threatened waters in the West will be an important discussion topic in the development of the workshop exit strategy.

Health Impacts and the Food Chain

Once mercury is deposited into water bodies, complex chemical reactions take place, creating harmful forms of mercury. The toxic forms bioaccumulate up the food chain eventually resulting in harm to humans that eat contaminated fish. The effects on humans can be quite severe depending on the state of the human and the level of mercury in the fish.

Water Chemistry

After mercury is deposited, transformation to harmful forms of mercury that are health risks to humans occur. Most mercury found in environmental media other than the atmosphere is in the form of inorganic mercury salts or organic compounds resulting from chemical reactions. Mercury concentrations in the air are usually low and do not pose a direct human health concern. Similarly, mercury in soils generally does not have an opportunity to methylate and has less chance of entering the food chain. However, mercury that gets into aquatic ecosystems through atmospheric deposition, direct

discharges from pollution sources or from soil runoff can be transformed into an extremely toxic organic methylmercury.

Methylation, the chemical reaction leading to methylmercury, is defined as the process by which the hydrogen atom of an organic compound of the hydroxyl group is replaced by a metal. It is through this process that mercury becomes part of an organic compound. Methylation generally occurs in the presence of water. Once organic, mercury as methylmercury, enters the aquatic food chain and is bio-accumulated. In an aquatic environment, methylation occurs primarily in the sediment or water column.

As with the chemistry of mercury in the atmosphere, the chemistry of mercury in the water also is connected to other important air pollutants. Research has revealed that the problems of acid deposition and mercury contamination are linked. Levels of mercury in fish tissue tend to be higher in more acidic water bodies (e.g., USGS 2000, Lutter and Irwin 2002). Acidity in the water is the result, in part, of deposition of sulfuric and nitric acids that are chemically formed in the air from emissions of sulfur dioxide and nitrogen oxides. A major source of these chemicals, as well as mercury, is the combustion of fossil fuels.

In addition to acidity, the concentration of dissolved organic carbon has a strong influence on the uptake of mercury by fish. Increasing the acidity and/or the dissolved organic carbon levels enhances the mobility of mercury in the environment, thus making it more likely to enter the food chain (e.g., USGS 2000).

Environments also can exaggerate the mercury problem. Environments that are known to favor the production of methylmercury include certain types of wetlands, dilute low-ph lakes in the Northeast and Northcentral U.S., parts of the Florida Everglades, newly flooded reservoirs, and coastal wetlands, particularly along the Gulf of Mexico, Atlantic Ocean and San Francisco Bay.

Food Chain

Toxic forms of mercury accumulate in an organism when rate of intake exceeds rate of elimination. Inorganic mercury can be absorbed, but at a much slower rate than methylmercury. Methylmercury accumulates much faster and is more difficult to eliminate because it bonds organically to the tissues of an organism. Elimination of methylmercury takes place very slowly, with “tissue half-lives” being on the order of months to years. Therefore an aquatic area of significantly high mercury concentration definitely will result in bio-contamination. Elimination of methylmercury in fish can take place so slowly that long-term reductions of concentrations are due mainly to the growth of the fish. In comparison, inorganic mercury compounds are eliminated relatively quickly because they are not actually bonded to living tissues.

Methylmercury is able to remain in animal tissue for very long periods of time and accumulates at an ever-increasing rate as it moves up the food chain. Accordingly, the threat of exposure is most severe to the animals at the highest levels of aquatic food chains and those animals and humans that feed on them. At the base of the food chain are phytoplankton and smaller benthic invertebrates that feed on algae and detritus. As these smaller animals are eaten, the mercury in their tissues is absorbed by their predators. Fish at the top of the food chain such as pike, bass, shark, and swordfish bioaccumulate methylmercury approximately 1 to 10 million times greater than dissolved methylmercury concentrations found in surrounding waters.

Humans are most likely to be exposed through consumption of fish, particularly larger predatory fish that contain higher levels of methylmercury. Other ways to be exposed are through methylmercury-contaminated drinking water and through dermal (skin) uptake through soil and water. Fish consumption is by far the dominant source of exposure (EPA, 2001).

Health Impacts

Mercury is absorbed through the GI track and easily enters the bloodstream where it is quickly distributed throughout the body. Important biological targets include unborn children in utero, nervous system, kidneys, and heart. Hair and blood are important biomarkers for mercury.

Neurotoxicological effects include tingling sensations, tunnel vision, blindness, ataxia, deafness and coma. Effects on unborn children include mental retardation, cerebral palsy, microcephaly, growth Retardation and death. Other effects include a reduced reproductive success, impaired growth and development and behavioral abnormalities. In addition, there are subtle decrements in motor skills and sensory ability at low levels. Tremors, inability to walk, convulsions and death can occur at high levels. Mercury also affects the immune system, alters genetic and enzyme systems, and damages the nervous system.

Several important epidemiological studies form the basis for determining when people are at risk. These include studies in England 1939; Iraq 1956, 1960, 1971-2,; Seychelles 1995, 1998; Faroe Islands 1997-1998; and New Zealand 1986, 1989. In some cases, exposures were high enough to cause death (NAS, 2000).

Populations at Risk

Small children and developing fetus are the most sensitive to the effects of mercury. Women of child-bearing age are the population of greatest concern. Children of women exposed to relatively high levels of methylmercury during pregnancy have exhibited a variety of abnormalities, including delayed onset of walking and talking, and reduced neurological test scores. Children exposed to far lower methylmercury exposures in the womb have exhibited delays and deficits in learning ability (e.g., EPA, 1997; NAS, 2000). The NAS report estimated that more than 60,000 children are born each year at risk for adverse neurodevelopmental effects due to in utero exposure to methylmercury.

Additional data are needed on the exposure levels at which humans experience subtle, but persistent adverse neurological effects. Data on immunologic effects and cardiovascular effects are not sufficient for evaluation of low-dose methylmercury toxicity (EPA, 2001a).

Harmful Levels

The new criterion for methylmercury in fish tissue is 0.3ppm wet weight (EPA, 2001a). Fish with concentrations higher than the criterion are considered contaminated. The reference dose (RfD) for exposure to methylmercury (i.e., fish consumption rate) is 0.0001 mg/kg-day. The reference dose is an estimate of a daily exposure to mercury that is assumed to be without an adverse effect.

Generally, a typical consumer who eats less than 10 grams of fish and shellfish per day with mercury concentrations averaging between 0.1 and 0.15 ppm is probably not at risk since the exposure would be lower than the reference dose. However, eating more fish than is typical or eating fish that are more contaminated, can increase the risk. This is particularly the case for a developing fetus. There is progressively greater concern about the likelihood of adverse effects even when the reference dose RfD level is not in excess (EPA, 2001a).

As a result of these concerns over mercury, the Food and Drug Administration (FDA) and EPA issued a joint advisory on fish from non-commercial sources in January, 2001. These fish are both caught and directly eaten by subsistence and recreational fishers. In that advisory, women who are pregnant or may become pregnant, nursing mothers and young children are advised to limit consumption of fish that may contain harmful levels of mercury. They are advised to limit consumption to one meal per week (i.e., six ounces of cooked fish per adult and two ounces of cooked fish per child).

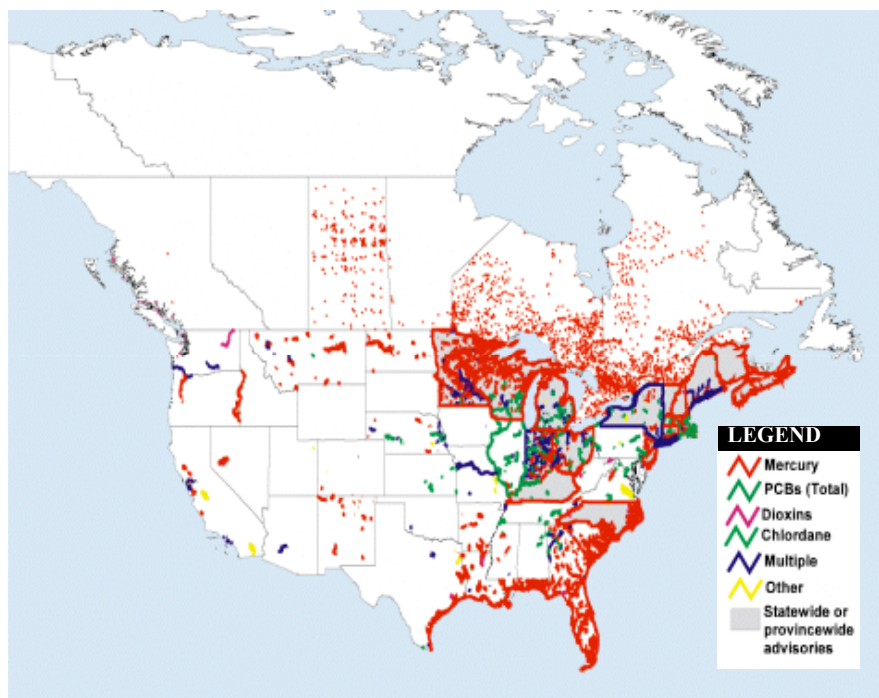
Health Impacts. The health impacts of mercury are linked to other atmospheric pollutants. For example, increasing the acidity and/or the dissolved organic carbon levels enhances the mobility of mercury in the environment, thus making it more likely to enter the food chain. Acid deposition comes from emissions of sulfur and nitrogen oxides. Combustion of fossil fuels are major sources of these chemicals, along with mercury. Better understanding these relationships is important to identifying co-benefits of different pollution reduction strategies. These connections need to be explored when developing the workshop exit strategy. In addition, given the ongoing concerns about health risks that may occur at even lower exposures, even lower emission reductions may be needed to protect health. The implications of these uncertainties regarding exposure also need to be considered.

Fish Advisories—Indicators of Risk

Fish and wildlife advisories provide an important way of alerting the public to potential dangers from mercury poisoning. The level of these alerts around the country also provide an indication of where in the U.S. impacts from mercury are highest. Finally, they provide a data set that can be quantitatively associated with emissions to develop an empirical relationship between emissions and impacts.

The states, territories, and Native American tribes have primary responsibility for protecting residents from the health risks of eating contaminated fish and wildlife. If high concentrations of mercury or other chemicals are found in local fish and wildlife, then the organizations may issue a consumption advisory for the general population. While the eastern U.S. has higher numbers of advisories, almost all of the western states have active advisories for specific water bodies. Figure 6 indicates all of the current advisories and their locations (EPA, 2001a). Specific mercury advisories for individual states can be obtained from EPA (EPA Fish & Wildlife Advisories). Advisories for Western states are summarized in Table 1.

Figure 6. Location of Waterbodies Under Consumption Advisories--2000



NOTE: This map depicts waterbodies where fish consumption advisories were in effect in 2000 based on information provided to the USEPA by the states in December 2000 and Canadian provinces in December 1997. Because only selected waterbodies are monitored, this map may not reflect the full extent of chemical contamination of fish tissues in each state or province. EPA US Fish and Wildlife Contamination Program

Source : NLFWA, December 2000

- Current advisories issued for:
 - Mercury
 - PCBs
 - Chlordane
 - Dioxins
 - 34 other chemicals.
- Advisories are in effect in:
 - 63,288 lakes, representing 23% of our Nation's lake acres
 - 9.3% of our Nation's rivers miles
 - 100% of the Great Lakes
 - 71% of coastline of contiguous 48 states.
- Number of advisories in the US in 2000 represents a 7% increase over 1999; 124% increase since 1993.
- 48 states, the District of Columbia, and 1 US territory and 8 Canadian provinces and 1 Canadian territory have fish advisories.
- 48 states and 1 US territory and 7 Canadian provinces and 1 Canadian territory have waterbody-specific advisories
- 14 states and the District of Columbia have statewide advisories and 2 Canadian provinces have provincewide advisories for lakes and/or rivers
- 15 states have all of their marine coastal waters under advisory.

Table 1. Mercury Advisories – Western States

State	Waterbody	Advisory Extent (county unless noted with *)	State	Waterbody	Advisory Extent (county unless noted with *)
AZ	Pena Blanca Arivaca Lake	90 Acres*	MT	Silver Creek Silver Creek Swan Lake Tongue River Reservoir Whitefish Lake Willow Creek Reservoir	20 miles* Near Helena* Entire lake* Near Harrison*
CA	Alamitos Creek & ponds Almaden Reservoir Black Butte Reservoir Calero Reservoir Clear Lake Guadalupe Creek & ponds Guadalupe Reservoir Guadalupe River & ponds Lake Berryessa Lake Herman Lake Nacimiento Lake Pillsbury San Francisco Bay Delta Region	Santa Clara Santa Clara Glenn & Tehama Santa Clara Lake Santa Clara Santa Clara Santa Clara Napa Solano San Luis Obispo Lake	NV	Carson River Lahontan Reservoir	Dayton to Lahontan Dam* All waters in Lahontan Valley*
CO	Lake Ladora Lake Mary McPhee Reservoir Narraguinnep Reservoir Navajo Reservoir Sanchez Reservoir	Rocky Mountain Arsenal* Rocky Mountain Arsenal* Entire Reservoir* Entire Reservoir* San Juan & Piedra arms* Entire Reservoir*	NM	Abiquiu Reservoir Avalon Lake Bear Canyon Reservoir Brantley Reservoir Caballo Reservoir Carlsbad Municipal Lake Charette Lakes Clayton Lake Cochiti Reservoir Conchas Reservoir Eagle Nest Lake Navajo Reservoir San Juan River San Juan River San Juan River Santa Rosa Reservoir Springer Lake Storrie Lake Stubblefield Reservoir Summer Reservoir Ute Reservoir	Rio Amba Eddy Grant Eddy Sierra Eddy Mora Union Sandoval San Miguel Colfax Rio Amba Hammond to Hogback* Hogback to Cudei* Cudei to Mancos River Guadalupe Colfax San Miguel Colfax De Baca Quay
ID	Brownless Reservoir		OR	Antelope Reservoir Cooper Creek Reservoir Cottage Grove Reservoir Dorena Reservoir East Lake Galesville Reservoir Jordan Creek Owyhee Reservoir Owyhee Reservoir Plat "I" Reservoir Snake River Willamette River	Entire reservoir* Entire reservoir* Entire reservoir* Entire reservoir* Entire lake area* Entire reservoir* Confluence to Idaho border* Entire reservoir* Upstream to Three Forks* Entire reservoir* OR/WA border south to Adrian* Columbia River south to Eugene
MT	Bighorn Lake Byrum Reservoir Canyon Ferry Reservoir Clark Canyon Reservoir Conney Reservoir Flathead Lake Fort Peck Reservoir Fresno Reservoir Georgetown Lake Hauser Reservoir Hebgen Lake Holtnar Reservoir Lake Elwell Lake Frances Lake Kooncanusa Lake Mary Ronan Martinsdale Reservoir Nelson Reservoir Seeley Lake	Entire Reservoir* Tiber Reservoir* Entire reservoir*	WA	Eagle Harbor	Bainbridge Island

In 2001, North Dakota issued a statewide advisory for mercury. A statewide advisory is issued to warn the public of the potential for widespread contamination of specific species of fish or wildlife in certain types of water bodies. North Dakota's advisory is for all lakes and rivers (EPA, 2002a).

Fish Advisories. Fish advisories for the West indicate that mercury is definitely a health issue in many western states. Exploring how to use fish advisories to characterize patterns of mercury impacts throughout the West needs to be part of the workshop exit strategy discussions.

Assessing Connections Between Sources and Impacts

Assessing the connections between mercury air emissions, concentrations of mercury deposited, concentrations of toxic methylmercury in water bodies, and the resulting health impacts from consuming contaminated fish is a major challenge. These relationships can be established by examining the available emissions, deposition and other relevant data, and drawing empirical relationships. They also can be estimated using air quality models of varying degrees of complexity.

Mercury Maps

The relationship between air deposition and fish contamination on a national scale is being determined by EPA through a program called Mercury Maps (EPA Mercury Maps). This tool relates changes in mercury air deposition to changes in mercury fish tissue concentrations using available data on deposition and contamination.

Mercury maps show:

- where fish tissue concentrations exceed new national methylmercury criterion (i.e., 0.3ppm methylmercury in fish tissue),
- how fish tissue concentrations relate to air deposition rates,
- which watersheds have air deposition as their sole significant source of mercury,
- which watersheds contain potentially significant sources of mercury loads other than air deposition, and
- estimates of mercury air deposition reductions needed to meet the new criterion.

An example of findings is presented in Figure 7. As can be seen from the figure, there are no geo-referenced fish data for most of the Western U.S. At this time, unfortunately, Mercury Maps have limited use in much of the West.

Estimated Percent Reductions in Air Deposition Load
Necessary to Meet New Methylmercury Criterion*
In Watersheds with No Other Significant Mercury Sources

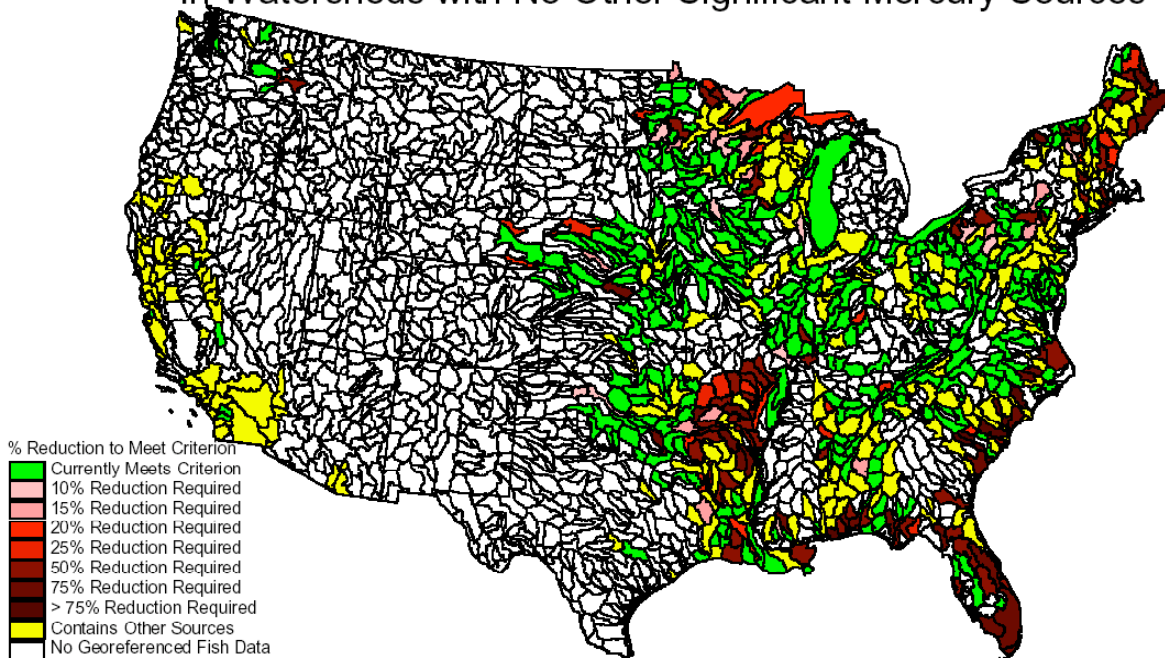


Figure 7. Mercury Maps

Mercury Maps. The exit strategy discussion should explore what analyses and data would be needed to apply the mercury maps approach in the West.

Assessment Studies and Findings

To reiterate the basics about mercury fate and transport, once emitted into the atmosphere, mercury is dispersed and transported through the air. Mercury in its various emitted forms chemically reacts at different rates. Eventually mercury is deposited and stored or transferred between the land and water. Mercury also is re-emitted into the air. In its reactive gaseous form, mercury is subject to faster removal from the atmosphere. This form is generally bound to airborne particles where it can be more quickly scavenged through precipitation and/or be dry deposited. Elemental mercury vapor has a

tendency to remain airborne and is not as readily deposited. Assessments generally attempt to consider all of these processes. In some assessments, assumptions are made about rates and significance of some processes in determining deposition to a particular water body under consideration.

Several studies indicate that the atmospheric transport of elemental mercury is a substantial contributor to mercury concentrations in land and water, especially in remote areas where atmospheric transport is the main mechanism of contamination. High concentrations of mercury have been found in fish taken from remote lakes throughout the world where there are no direct discharges of mercury (EPA, 1997; Fitzgerald et al 1998).

EPA's 1997 Mercury Study Report to Congress also discussed a plausible link between anthropogenic releases of mercury from industrial and combustion sources in the U.S. and methylmercury in fish. The report noted that background levels of fish methylmercury may also consist of mercury from natural sources, as well as mercury which has been re-emitted from the oceans or soils where the original sources could have been natural or anthropogenic. Given the current scientific understanding of the environmental fate and transport of mercury, it is difficult to quantify exactly how much of the methylmercury in fish consumed by the U.S. population in various parts of the country is the result of U.S. emissions relative to other sources (e.g., EPA 1997; Seigneur et al 2001).

The relative contributions to mercury deposition from near-by sources versus long range transport has been explored in a number of studies and the findings regarding the relative importance of local versus regional and global emissions in determining mercury source-receptor relationship in the U.S. vary (Hanisch, 1998). Some field measurements of oxidized mercury near the ground in close proximity to power plants indicate that sources can have local impacts (Lindberg and Stratton, 1998). Similar indications of contributions of emissions to nearby deposition have been found in South Florida (Dvonch et al, 1999). The more recent synthesis of the Everglades assessment work

indicate that atmospheric deposition account for greater than 95% of the external load of mercury. The relative proportions of local and long-range transport of mercury to the Everglades remain an open question (Atkeson and Parks, 2002).

Analyses for European countries also are varied. However, a recent European study shows that, for several countries, over 50% of the country's mercury deposition is attributed to emissions within the country (EMEP, 2003). Germany, Poland and Greece all indicate over 50% of the mercury comes from within the country. Belgium, Bulgaria, Switzerland, Czech Republic, Denmark, Spain, France, Hungary, Italy, Luxembourg, Portugal, Romania, U.K. and the Ukraine all indicate that between 25-50% of the mercury deposition originates from within the country.

Recent studies estimate that 47% of the mercury deposited in the northeastern U.S. comes from within that region, 30% from other U.S. sources and 23% from global sources. Source-receptor model findings indicate that mercury in its oxidized and particulate forms are deposited in areas close to sources. Source-receptor modeling studies also are showing that Asian emissions account for only 10-20% of deposition in the west coast and that non-anthropogenic sources contribute only 4-7% to deposition in the eastern U.S. and 10-12% in the West (EERC-Air Quality II Conference Summary, 2000).

More complex chemical transport and transformation models are beginning to be used to determine mercury concentration and deposition patterns around the world. These models can explore and quantify source-receptor relationships in more detail and can assess the effectiveness of emission reduction strategies in the future. However, these models are limited by quality of emissions data and understanding of the chemical and physical processes determining mercury behavior in the atmosphere. Speciation of the mercury emissions, mercury atmospheric chemistry, and deposition processes remain major sources of uncertainty in such models.

Seigneur et al (2001) present a global-continental-regional modeling study of the atmospheric fate and transport of mercury. Preliminary simulations indicated similarity in patterns of high emissions and high concentrations and deposition, suggesting the influence of sources on nearby areas. Figure 8 provides an illustration of total annual mercury deposition for the U.S. Similar patterns have been found in recent EPA modeling studies (Bullock and Brehme, 2002). More detailed studies of contributions from different global sources to receptor areas in the U.S. are suggesting that natural sources of mercury are more significant than previously suspected (e.g., EEEEC—Air Quality III Conference Summary, 2003; Levin, 2002).

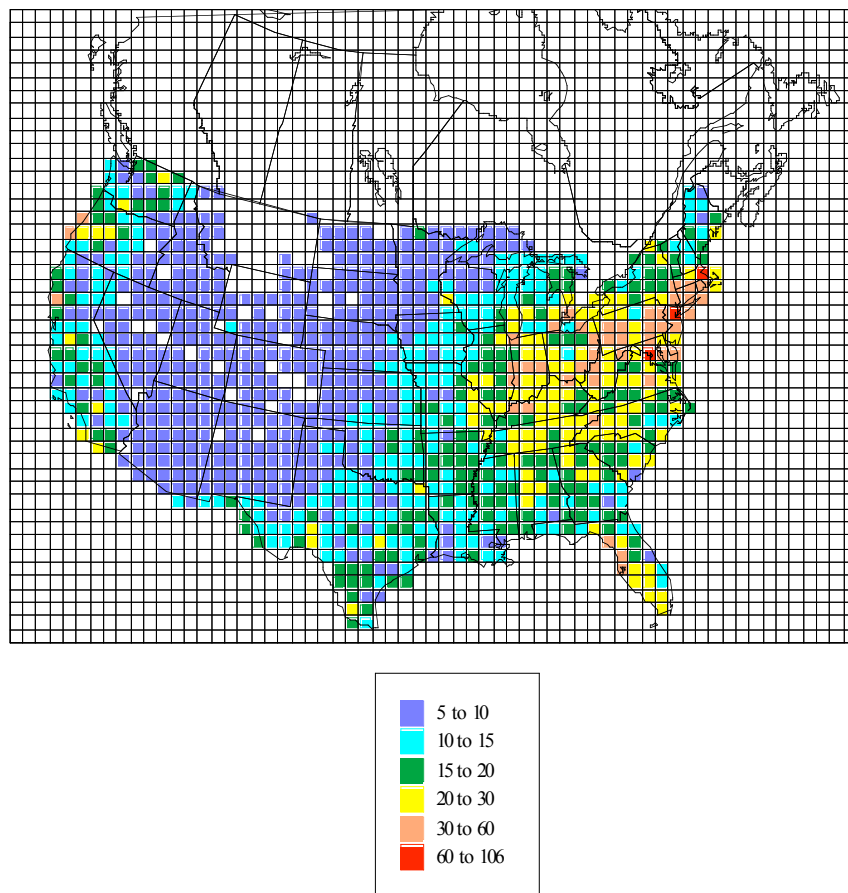


Figure 8. Total annual mercury deposition flux in micrograms/square meters (Seigneur et al)

State specific and reservoir specific source attribution studies also have been recently conducted. A comprehensive modeling assessment was used to analysis of

contributions of global and regional sources to mercury deposition at three lake areas in New York state. The study analyzed the relative importance of deposition at several lake areas in New York from sources within New York vs. sources in Canada, Mexico, other parts of the U.S., South America, Africa, Europe, Asia, Oceania, and natural sources (Seigneur et al, 2002). The study found that for the three receptor areas studied in New York, the contributions of mercury from within New York state varied between 11-21%. Natural sources contributed between 18-24% and the rest of the U.S. contributed between 25-48%.

Another recent modeling analysis, developed as part of the EPA's pilot programs (EPA, 1999) looking at the relationships between air deposition and specific water body contamination, explored the relative importance of different source categories to mercury deposition to specific lakes in Wisconsin. In this study, the Wisconsin sources were broken down into coal utilities, industrial boilers, chlor-alkali plants, medical waste, municipal waste, and others. Contributions from each other state, Canada, and re-emission sources were also tracked. An example of the analysis results is shown in Figure 9 (Meyer, 2002). This study indicates that most of the deposition comes from background sources that are not included in anthropogenic U.S. and Canadian sources.

Contributions to total mercury deposition at the Devil's Lake site, w/ and w/o background

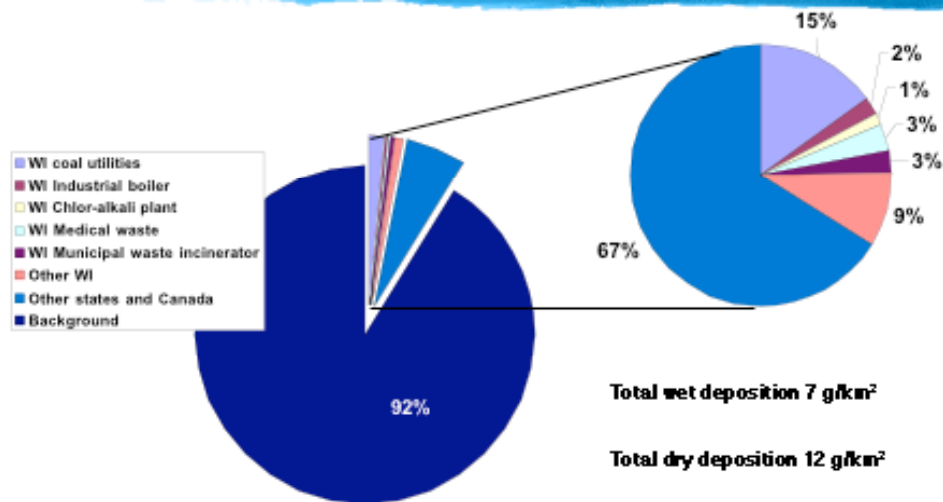


Figure 9. Example of source - receptor analysis for Mercury air deposition at Devil's Lake, Wisconsin

Assessment Approaches and Findings. A variety of approaches have been used to explore relationships between source areas and deposition to contaminated water bodies. Generally, the natural and distant sources seem to play a role in many areas. The extent to which this will be the case for Western waters will need to be considered when developing the workshop exit strategy.

Air Deposition Assessment Strategies

As has been illustrated in these examples of air deposition studies, a variety of approaches can be used to estimate contributions of mercury air deposition sources to threatened water bodies. Assessment strategies vary in terms of level of detailed source attribution desired, data requirements and availability, and complexity of models used. Often overall cost of the analysis also is a determining factor. The development of strategies based on assessment questions to be answered, information and model availability, and resource considerations have been discussed in detail in recent EPA

handbooks on ecological assessments and assessments of water body contamination in particular (EPA, 2001b; EPA, 2001c).

Assessment strategies can be characterized as:

- data analyses where origins of the deposited mercury are estimated from observations,
- screening analyses that use simple models to relate specific sources to deposition, and
- complex model simulations based on chemical and physical process models that can provide estimates of source contributions from a wide range of sources.

The simpler modeling assessment generally considers the relationship of a specific source or source area to deposition at a particular receptor such as a water body. The more complex modeling analysis can consider relative contributions from several emission sources within the region. The most comprehensive analysis takes into account the contributions from global as well as regional and local sources and can be used to examine deposition to multiple receptor areas. The data and other requirements, as well as the assumptions regarding processes not directly taken into account in the assessment, vary considerably for the different approaches.

The more complex modeling studies are particularly valuable for areas where deposition data are sparse. The models can predict deposition levels in areas where there are no data. The more sophisticated approaches also are helpful for establishing the relative importance of a wide range of sources on different temporal and spatial scales. Models that are based on chemical and physical processes rather than observational analyses also are very useful for examining the outcomes of different emissions change scenarios.

Assessment Strategies. Modeling studies provide useful information on the relative importance of different sources to deposition at a particular site. However, because of the uncertainties in characterization of chemical and deposition processes and the emission inventories, there are uncertainties in the analysis results themselves. These must be taken into account when selecting and using the modeling tools to

determine actual load reductions that may be needed to protect a particular water body. The workshop exit strategy discussions will need to explore opportunities for using more comprehensive modeling for the western water contamination issues. The workshop also will need to identify situations where simpler approaches would provide useful screening analyses.

TMDLs: Lessons Learned and Learning

High water quality is an extremely valuable commodity and, as already underscored throughout this review, is intimately linked to air quality. Across the nation, water and air quality programs are undertaking multi-media approaches to address unacceptable levels of mercury and other pollutants in various water bodies. Water quality programs are charged with assessing and improving affected water bodies and are often legally required to do so through the Clean Water Act's Total Maximum Daily Load (TMDL) process. Air quality programs are charged with assessing the role of air pollution sources as contributors to the contamination of affected water bodies. Air quality programs have responsibilities to provide support to water quality programs regarding atmospheric mercury deposition rates, monitoring, modeling, identification of emission sources, inventory development and maintenance, and control strategies for air pollution sources.

As discussed below, the TMDL process shows how strategies are being developed to protect water bodies. The approaches being used and questions being asked for current Colorado TMDL illustrate the challenges in developing a successful TMDL. Other Western mercury TMDL processes and studies dealing with air deposition underscore the challenges involved in developing Western assessments. Regional approaches to water quality concerns, as exemplified by experiences in the northeastern U.S., provide promising alternatives for dealing with air deposition sources that extend beyond the immediate vicinity of a water body.

TMDL Process

When states and local communities identify problems in meeting water quality standards, a TMDL often is part of a plan to address the water quality problems. EPA water quality standards are based on maximum contaminant levels of inorganic mercury in drinking water (0.002 mg/L) and levels of methylmercury in fish tissue (0.3 ppm).

Actual fish consumption advisories issued by EPA, Food & Drug Administration, states, and tribes are related to methylmercury in fish. For reference, the methylmercury reference dose (RfD) established by EPA is 0.0001 mg/kg-day.

A TMDL provides an estimate of pollutant loading reductions needed to restore the beneficial uses of the water body at risk. Frequently it is expressed as the total mass or quantity of a pollutant that can enter the water body within a unit of time. In most cases, the TMDL determines the total allowable loading for a pollutant, like mercury, and divides it among the various known sources of that pollutant that are contributors to the waterbody. The TMDL also accounts for natural background sources and provides a margin of safety for the determination of necessary load reductions.

The challenges of addressing mercury contamination are twofold. First the levels of mercury loadings that are leading to the adverse condition (i.e., contaminated fish) need to be established. Second, the relative importance of different sources of mercury need to be determined. Mercury can enter a waterbody through air deposition or direct discharge. Air deposition can be the result of anthropogenic and natural processes.

TMDL Process. Identifying necessary steps for determining the relative importance of different air deposition vs. other pathways, that support of the development of a successful TMDL, will need to be a key focus of the workshop exit strategy discussions.

Mercury TMDL for McPhee & Narraguinnep Reservoirs, Colorado

The Colorado Department of Public Health and the Environment (CDPHE) has identified McPhee and Narraguinnep Reservoirs as not supporting their designated uses due to the presence of elevated fish tissue concentrations of mercury that have resulted in the posting of Fish Consumption Advisories. As a result, a TMDL (CDPHE, 2002) is being developed to address this concern. The purpose of the TMDL is to provide an estimate of pollutant loading reductions needed to restore the beneficial uses of these two

reservoirs. The U.S. EPA Region 8 is supporting CDPHE in the development of this TMDL. The reservoirs are pictured in Figure 10.

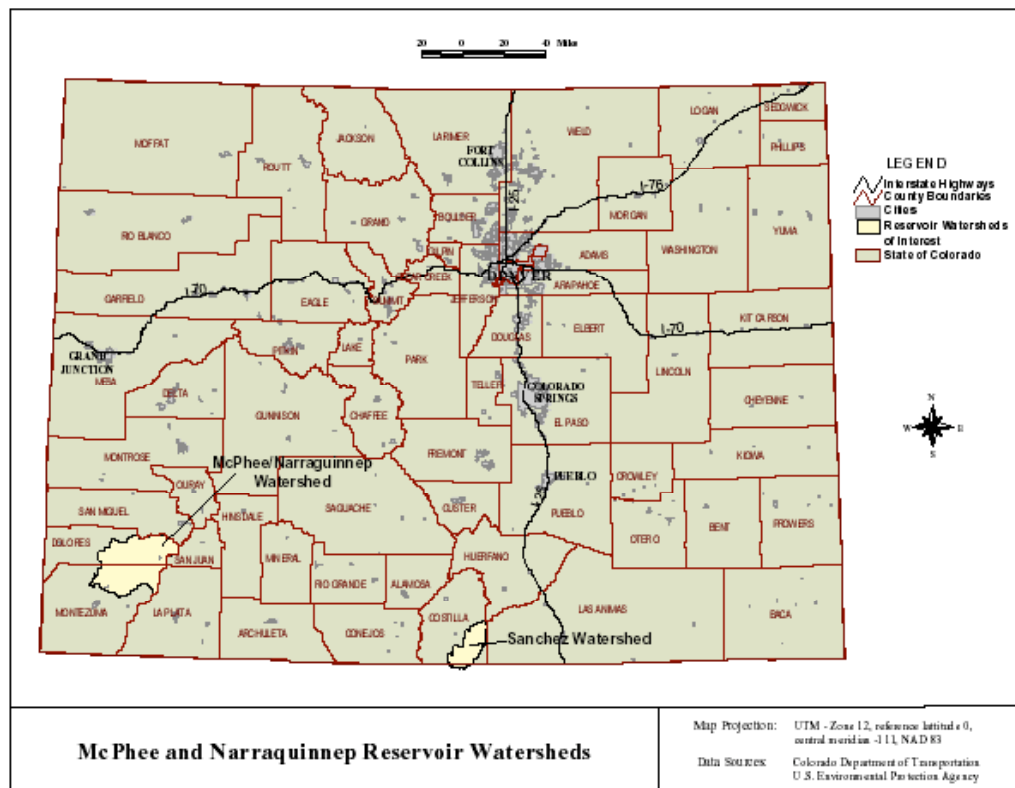


Figure 10. Colorado TMDL Reservoir Locations

The TMDL is following a phased approach, which acknowledges that additional data and analysis is needed to establish a TMDL that will achieve, with greater certainty, the applicable state standards. It is important to note that the phased approach was used for this TMDL because numerous data gaps and uncertainties were identified in Phase 1 and only rough estimates of actual contributions of mercury to the Reservoirs from both point and non-point sources could be identified. To address these uncertainties, Phase 1 includes an assessment of the data gaps identified in the initial allocation estimates and a plan for additional data collection and analyses. The Phase 1 TMDL has been completed

and the CDPHE and EPA Region 8 are now seeking advice on how Phase 2 should proceed. This advice will be part of the exit strategy developed at the end of the workshop.

Phase 1 of the TMDL consisted of allocating available loading capacity of the Reservoirs (the maximum rate of loading that would be consistent with achieving designated uses) to point sources, non-point sources, and a margin of safety. The preliminary mercury loading capacity estimates are 2592 grams per year for McPhee Reservoir and 39 grams per year for Narraguinnep Reservoir.

The potential sources of mercury include direct atmospheric deposition from near and far-field sources and transport into the Reservoirs from the watershed. For Narraguinnep, mercury in diversions from McPhee must also be considered. Sources in the watershed include mercury in the parent rock, mercury residue from mine tailings and mine seeps, point source discharges, and atmospheric deposition and storage in snowpack, which then runs off into the Reservoirs. Monitoring of streams and stream sediments typically reflects the combined impact of a number of these watershed sources. Air deposition sources include coal-fired power plants, waste incinerators, cement and lime kilns, smelters, pulp and paper mills, and chlor-alkali factories. Contributions from all of these sources plus forest fires need to be considered.

Estimation of external loads, particularly due to atmospheric deposition, is highly uncertain. Previously, no direct measurement of atmospheric deposition of mercury is available at or near the reservoirs. The new mercury deposition site at Mesa Verde should help future assessments. For Phase 1, estimates of mercury deposition were made using nitrate and sulfate deposition as a surrogate and simple screening techniques were used to explore the importance of large power plant point source emissions. Analyses of potential contributions from other sources were not examined in detail.

To better assess the relative importance of external loads several data collection steps are scheduled for Phase 2:

- Collect sediment and water chemistry data from the new sites.
- Collect deposition data from the new MDN monitoring station in Mesa Verde.
- Collect additional data on mercury in snowpack within the McPhee area.
- Collect additional data from sediment cores from Narraguineep.

In addition, the influence of other anthropogenic point sources (e.g., smelters and gold mines) in addition to the coal-fired power plants, forest fires, and related re-entrained mercury from cinnabar soils needs to be assessed. The Phase II effort definitely will move away from the weaker sulfate and nitrate surrogate method used to estimate air depositions in the first phase of the TMDL. It also will be important to determine total deposition (i.e., both wet and dry deposition) in order to assess more completely the air deposition pathway to mercury contamination in the Reservoirs. To better determine these external loading and the relative importance of the different sources, particularly in view of the many data gaps, it has been concluded that Phase 2 needs to consider the use of a more comprehensive, non-linear atmospheric modeling system.

Colorado TMDL. As part of this workshop exit strategy, CDPHE and EPA Region 8 are seeking advice on their planned data collection, how best to use this data, additional information that should be collected, and type of modeling approach to use to determine relative importance of sources.

Western TMDLs and Mercury Air Deposition Studies

Mercury TMDLs are underway for almost all of the western states. Here is a listing of many of them.

Arizona -- Arivaca and Pena Blanca lakes. 6 other water bodies are listed.
California -- San Francisco Bay Estuary, the San Diego Creek, Clear Lake and Newport Bay. Almost 4 dozen are listed as impaired.

Colorado – Narraguinep and Sanchez Reservoirs plus 5 other water bodies are listed.

Idaho -- "submittal pending" on the Snake River/Hells Canyon. Jordon Creek and Brownlee Reservoir are listed as impaired.

Montana – Over four dozen are listed as impaired.

Nevada – Carson River.

New Mexico – Slightly more than four dozen are listed as impaired.

North Dakota – Seven rivers are listed as impaired.

Oregon -- Willamette River. Owyhee River is listed as impaired.

South Dakota – Squaw and Spearfish Creeks, Whitewood & Deadwood Creeks.

Washington -- Bellingham Bay. About 3 dozen are listed as impaired.

The San Francisco Bay Estuary atmospheric deposition pilot study determined deposition levels from observational data analysis (San Francisco, 2001). For studies where information is already readily available, use of deposition data to assess air deposition is the general approach.

Recently, the Cheyenne River Sioux Tribe and the EPA initiated a project to characterize mercury contamination in a variety of water bodies in North Dakota. Atmospheric deposition is suspected to be an important contributor. This program involves extensive sampling and application of the EPA Watershed Characterization System and Mercury Cycling Models. (Edgar, 2003).

TMDL development for Oregon's Willamette Basin includes investigating sources of mercury. The extent of atmospheric deposition remains an important data gap. (Rubin, 2003)

Western TMDLs. There are not many western mercury deposition studies being conducted as yet in the context of the TMDL process. As part of the workshop discussions, a more comprehensive listing of ongoing studies, resources, contacts and challenges in the western states needs to be developed.

Regional Approaches

When air deposition is determined to be a major determinant of mercury contamination in a water body and there are no clear dominant air emission sources of the mercury deposition, then broader assessments are needed. The current approaches being used to address mercury in the northeastern U.S. provide an example of such an expanded approach.

The New England (Northeast) Mercury “TMDL” project has a number of collaborating state and federal agencies that deal with air, water and waste. The objectives are to develop a regional mercury TMDL, link mercury loading to mercury in fish, identify natural and human factors contributing to risk, estimate mercury reductions needed to meet the 0.3 ppm methylmercury in fish tissue limit, evaluate management options, and help optimize future data-collection activities.

Regional Approaches. TMDLs, as the main mechanism for establishing necessary reductions to achieve water standards, are different for water bodies that are subject to significant air deposition. Determining the relative contributions of different air emission sources remains a large challenge for western states that are beginning to evaluate the importance of air deposition. As illustrated by TMDL efforts in other parts of the country, regional approaches may be the best way to achieve water protection goals in many areas.

Mercury Reduction Strategies

The growing realization that air deposition is a major factor leading to contamination in water bodies is leading to careful examination of mercury air emissions management strategies at multiple levels from state to national to international. Options for further reductions in mercury air emissions from coal-fired power plants is a particular focus in the U.S., given the importance of this mercury source. Because of the national and even global nature of mercury deposition, increased attention is being paid to new strategies and agency roles in developing these broader based approaches to dealing with the mercury issue.

Regulations and Reduction Programs

Momentum for increased regulation appears to be growing given the recent studies that report on the sources of and harm due to mercury emissions. Two out of the four top sources of mercury pollution (municipal waste combustors, medical waste incinerators) have already been addressed through federal regulation. Regulation of the top source, coal burning utility boilers, is now the current focus. The following section summarizes current mercury regulations at the federal and state level (Mercury Policy Project, 2002), outlines EPA plans for addressing coal-fired utility mercury emissions in the near term (Utility Air Toxics MACT 2002), and summarizes proposed legislation targeting mercury emissions from coal-fired utilities. Finally, activities on the international level are noted.

Federal Regulations

- **Municipal Waste Combustors:** On October 31, 1995, the EPA issued final regulations for Municipal Waste Combustors (MWC's). These regulations were designed to reduce emissions from MWC's from 90% levels by this year (2000). Every new MWC must comply with these regulations at startup and every existing MWC must comply by December 2000.

- **Medical Waste Incinerators:** On August 15, 1997, the EPA issued emission standards for Medical Waste Incinerators (MWI's), which were designed to reduce emissions from these sources by 94% from 1990 levels. All new MWI's must comply at startup and all existing MWI's must comply by September 2002.
- **Mercury Cell Chlor-alkali Plants; Ore Processing Facilities:** 40 CFR 61.01 limits emissions from mercury ore processing facilities and mercury cell chlor-alkali plants to a maximum of 2,300 grams per 24 hour period.
- **Hazardous Waste Combustors:** On September 30, 1999 EPA enacted revised emissions standards for hazardous waste incinerators, hazardous waste burning cement kilns, and hazardous waste burning lightweight aggregate kilns. These regulations were enacted pursuant to authority granted by the Clean Air Act (CAA) and the Resource Conservation and Recovery Act (RCRA). The standards limit various emissions including emissions of toxic metals, one of which is mercury. The EPA anticipates that this regulation will cut mercury emissions by 50% from 1990 levels. RCRA also regulates airborne emissions of mercury produced by the burning of hazardous waste in boilers and industrial furnaces.

State Regulations

- **Florida:** Florida set standards to reduce mercury emissions from municipal solid waste incinerators to 65 micrograms/m³.
- **Maine:** Maine mandates that no air emission source may emit mercury in excess of 100 pounds per year after January 1, 2000, and 50 pounds per year after January 1, 2004.
- **Minnesota:** Minnesota established goals of reducing total mercury releases into the air and water from both new and existing sources by 60% from 1990 levels by December 31, 2000, and by 70% from 1990 levels by December 31, 2005. In addition, new

incinerator permits with mercury limits will require air monitoring systems and periodic stack testing.

- New Jersey: New Jersey has set emissions standards for municipal waste incinerators to 65 micrograms/m³, with further reductions to be phased in.
- Ohio: Ohio is currently considering mandating the installation of mercury emission control equipment.
- Wisconsin: In Wisconsin, MWI's with capacity greater than five tons per day must be tested for mercury during the first 90-day period of operation and once the following year. Additionally, the Wisconsin Department of Natural Resources (WDNR) is exploring the implementation of a cap and trade program. Under the plan, WDNR would establish a cap for mercury emissions that would reduce emissions by 20% by 2005 and a 50% by 2010. Reductions would be based upon a baseline set by the average annual emissions during the three years prior to the establishment of the program. Sources unable to meet the reduction limits would have a limited ability to purchase excess reductions from sources whose reduced emissions exceeded the required amount.

EPA Plans Addressing Utilities

EPA has announced its finding that regulation of Hazardous Air Pollutant (HAP) emissions from oil- and coal-fired electric utility steam generating units is necessary and appropriate. Mercury is a HAP associated with these utility emissions. The EPA decision resulted from assessments dictated by the mandate given to EPA by Congress in section (112)(n)(1)(A) of the Clean Air Act, as amended. In this, EPA was to perform a study of the hazards to the public health reasonably anticipated to occur as a result of HAP emissions by electric utility steam generating units. The results of the study were released in a Report to Congress on February 24, 1998. The EPA was also required to determine whether, based on the results of the study and any other applicable information, regulation of HAP emissions from the industry was appropriate and necessary. On December 14, 2000, the EPA announced that it had

found that such regulation is warranted and a project to develop emission regulations under section 112 has begun. Proposal of emission standards will be on or before December 15, 2003, with promulgation following on or before December 15, 2004. These are to become effective in February 2005. Installation of mercury emission control technology will be required no later than three years after finalized regulations go into effect on February 2008.

For control of HAPs, the Clean Air Act Amendments require the maximum degree of reduction in emissions of the required pollutant. These controls, known as the maximum achievable control technology (MACT) standards, are based on the average emission level achieved by controls on the best performing 12 percent of existing sources, by category of industry and utility sources.

The Utility MACT Working Group was formed to provide input to EPA regarding Federal air emissions regulations for coal- and oil-fired electric utility steam generating units. The Working Group identified the following issues which EPA must consider and resolve in its drafting of the utility MACT: subcategories for mercury, floor levels for mercury, beyond the floor levels for mercury, format of mercury standard, compliance method (monitoring) for mercury, compliance time, non-mercury HAP, and oil-fired units.

New Legislation and Initiatives

In the U.S., there were approximately 50 mercury-related bills introduced in the states (California, Connecticut, Indiana, Maine, Maryland, Massachusetts, Michigan, Minnesota, Nebraska, New Hampshire, New Jersey, New York, Oregon, Rhode Island, Texas, Vermont and Wisconsin) in 2001, with at least 10 bills passing in six states between August 2000 and August 2001. Only one bill, being considered in Wisconsin, specifically deals with mercury emissions from coal burning plants. As of July 2002, there were several laws dealing with multi-pollutant emissions. New Hampshire, Connecticut, Massachusetts, North Carolina, New York, Texas and Illinois all have laws addressing two or more of the four major pollutants (nitrogen oxides, sulfur dioxide, mercury, and carbon dioxide). All have been enacted except for Massachusetts', which was issued in 2001, and New York's, which has been proposed.

An extensive review of current mercury reduction activities throughout the U.S. illustrates the effectiveness of local and statewide efforts to reduce mercury pollution from a variety of sources (National Wildlife Federation, 1999 and 2002). Of particular note are the steps being taken in Washington, Wisconsin and Massachusetts. Washington, in response to strong citizen concern, developed a comprehensive plan to eliminate all persistent, bioaccumulative toxic chemicals. This plan provides an overall context for mercury reduction efforts that is very different from states where mercury is targeted as a single issue. Much further along than most states in addressing mercury, Wisconsin has a community-oriented source/waste reduction approach and has shied away from creating regulatory measures. Massachusetts has built on the northeast regional commitment to reduce mercury and has taken a regulatory approach at the state level to further reduce mercury from products and waste.

In addition to EPA's development of the mercury MACT standard, which was discussed in a previous section, several actions to control mercury are taking place at the federal level. Senate Bill 556, "The Clean Power Act", introduced by Senator Jeffords, recently passed the Senate Environment and Public Works Committee. The "Clean Power Act of 2001" takes advantage of the multi-pollutant nature of coal burning utility emissions to achieve multiple benefits. It seeks to reduce power plant emissions of SO₂, NO_x, mercury and CO₂, eliminate "grandfather" exemptions for older power plants, allow market mechanisms to control emissions and ensures safe disposal of mercury and other hazardous wastes.

Senator Carper introduced the Clean Air Planning Act in October 2002. It also takes a market-based approach that would aggressively reduce emissions of sulfur dioxide, nitrogen oxides, carbon dioxide and mercury from power plants.

In February 2002, the White House announced the Clear Skies & Global Change Initiative. The Clear Skies Initiative proposes to cut SO₂, NO_x and mercury emissions using market based cap and trade programs (Clear Skies, 2002). The Clear Skies Initiative was reintroduced in the Senate in 2003.

International Cooperation

At the international level, the U.S. and Canada Great Lakes Water Quality Agreement calls for the elimination of mercury from the Great Lakes. The U.S. and Canada also joined Europe in signing a 1998 Protocol to the Convention on Long-Range Transboundary Air Pollution to reduce mercury emissions below 1990 levels. In addition, the United Nations Environment Programme recently called for a global study of mercury impacts on human and environmental health. These actions are the first steps toward an international agreement similar to the Persistent Organic Pollutants (POPs) Treaty (e.g., EEEEC, 2003).

Quicksilver—Linking Air and Water Quality

Nationwide, there are a significant number of contaminated water bodies that are affected by mercury deposition from sources around the country and the world. In light of the growing concern over these extensive contributions of air emissions to mercury contamination, a new group (the Quicksilver Caucus) has formed to develop a national mercury reduction strategy to achieve water quality standards (Quicksilver, 2003).

The goal of the national strategy is the significant reduction and where possible, elimination of anthropogenic emissions of mercury, in order to reduce current levels of mercury to attain the goals established in the federal Clean Water Act and state Water Quality Standards. This goal is consistent with the Bi-National U.S-Canada agreement regarding persistent toxic substances (e.g., mercury). It is also consistent with the National Governors' Association Comprehensive National Energy Policy and with the Northeast States and Eastern Canadian Premiers Framework for Action.

The straw person proposal has just been released and is under discussion. The blending of the standard TMDL approaches with this national based strategy is one major challenge ahead.

Regulations and Strategies. *The ongoing discussions regarding the MACT standards for mercury and the different approaches to multi-pollutant regulations bring up important considerations for the workshop: the level of mercury emissions reductions that may be needed to protect western waters, how best to achieve these reductions, and the approach to dealing with additional emission reductions that may be needed outside of vicinities of threatened waters and perhaps, even outside of the U.S.*

Mercury Control Options

Mercury air emission reductions that may be needed in order to protect threatened waters can be achieved using a variety of strategies. Reductions in mercury emissions from the major sources (coal-fired boilers, municipal waste combustors (MWCs), medical waste incinerators (MWIs), and chlor-alkali plants) can be achieved through pollution prevention (e.g., process changes, fuel switching) or “end of the pipe” removal of mercury from the effluent. For coal-fired utilities, particular attention is being given to technologies that are effective, or could be made more effective, in reducing other pollutants as well as mercury. Emissions trading also is an alternative management strategy being considered. This report focuses on the technological control options for reducing mercury from coal-fired utilities.

Pollution Prevention for MWCs, MWIs and Chlor-alkali Plants

An important control measure for MWCs and MWIs is pollution prevention, which includes *product substitution* – to decrease the volume of mercury containing products requiring disposal, and *materials separation* – to separate the mercury containing waste from other waste prior to combustion.

Product substitution is the replacement of mercury with an appropriate substitute or the use of low-mercury constituents. Some mercury-containing products such as batteries, lamps, and some medical equipment could be produced with lower mercury content or even without it, by changing technology at quite reasonable costs. This strategy proved its usefulness with batteries when a number of states issued regulations that limited or even banned the amount of

mercury allowed in batteries. That in turn led to the introduction of technologies, which substituted mercury in batteries for less dangerous materials.

Material separation is an appropriate approach for processes where mercury-containing products are disposed of by incineration, or where mercury can be reduced in the fuel prior to the fuel being combusted (e.g., medical waste incineration). Removing mercury-containing products such as batteries, fluorescent lights and thermostats from the waste stream can reduce the mercury input to waste combustors without lowering the energy content of the waste stream. The mercury removal efficiency varies depending on the extent of the separation. Separating high volumes of materials containing mercury in negligible concentrations (paper, plastic, paint, etc.) counters the intended purpose of the combustion process, which is to disinfect and reduce the volume of waste materials. The separation of other materials that contain higher concentrations of mercury, but make up only a very small portion (less than 1 %) of the total waste stream, can reduce mercury input to a combustor without removing any of the energy content of the waste stream. To evaluate a materials separation program, the feasibility and costs of separating a particular material need to be compared with the mercury emission reduction achieved. Furthermore, the current and future mercury reduction achieved by separating certain materials needs to be considered since the mercury content of some items such as household batteries has already declined considerably.

Process modification is a viable strategy for chlor –alkali plants, which use the mercury cell process. The plants can transfer to a mercury-free membrane cell process. Membrane cell processes requires less energy, and allows avoiding the cost of disposing mercuric wastes, thus creating additional incentives for chlor-alkali plants. In 1994 about half of these plants used mercury-free technology.

Pollution Prevention for Coal Utilities—Cleaning, Blending and Fuel Switching

Coal cleaning is usually applied to certain types of coal to increase its quality and heating value, but it also achieves significant reductions of mercury concentration in coal. Approximately 77 % of the eastern and mid-western bituminous coal shipments are cleaned in

order to meet customer specifications for heating value, ash content and sulfur content. Western coals generally have much lower mercury content than these coals. Any reduction in mercury content achieved by coal cleaning results in a direct decrease in mercury emissions from the boiler. The mercury removed by cleaning processes is transferred to coal-cleaning wastes, which are commonly found in the form of slurries. However, these slurries become another source of emission. Currently there is no available data to estimate the amount of emissions from them.

The reduction of mercury in coal due to coal cleaning varies by type of coal and the coal cleaning procedure applied. EPA data, which covers a number of different coal seams (with particularly high mercury contents) in four states (Illinois, Pennsylvania, Kentucky and Alabama), indicates that mercury reductions range from 0 to 64 %, with an overall average reduction of 21 %. It is expected that significantly higher mercury reductions can be achieved with the application of emerging coal preparation processes. For example, in one bench-scale study of EPA, five types of raw coal were washed by conventional cleaning methods followed by column froth floatation or selective agglomeration. Conventional cleaning and column froth floatation reduced mercury concentrations from the raw coals 55% on the average. Conventional cleaning and selective agglomeration reduced mercury concentrations from the raw coals 68% on average. In a second bench-scale study in which three types of coals were cleaned with a heavy-media-cyclone (a conventional cleaning method) followed by a water-only-cyclone and a column froth floatation system, mercury concentrations in the raw coal were reduced by as much as 65 %.

Several power plants in the West use compliance or cleaned coal as part of their sulfur dioxide control strategy. This probably is helping reduce mercury emissions to some extent at these facilities.

Coal Blending involves blending higher mercury-containing coals with lower mercury-containing coals to reduce mercury emissions. Such a practice is similar to blending high and low sulfur-containing coals in order to meet sulfur dioxide emission limits. However, coal blending for mercury control is not yet a proven control strategy. Changes in the electrical resistivity and amount of fly ash resulting from coal blending could reduce particulate (PM) capture efficiencies by electrostatic precipitators (ESPs) and subsequently lead to increased emissions of PM and HAP metals. These effects on ESP performance can be addressed by gas

conditioning and/or modifications to the ESP. Blending for mercury control could also increase levels of other HAPs or sulfur dioxide. Another uncertainty with coal blending for mercury control would be the possibility of changing the distribution of the elemental and oxidized forms of mercury that could affect mercury control with existing control devices. Another factor is that the blending of two different coals might change the higher heating value of the resulting mixture, with subsequent effects on the quantity of fuel required for combustion.

Fuel Switching, another preventive option for coal-fired boilers, involves switching to coals that have lower mercury content or switching to other fuels. The ultimate fossil fuel switching would entail moving over to the cleanest fossil fuel, natural gas, which produces almost zero mercury emissions and much lower emissions of other key pollutants (e.g., sulfur dioxide, nitrogen dioxide, carbon dioxide and particulates) as well. Use of renewable energy, which is completely free of mercury and other key pollutant emissions, is another fuel switching option. The fuel switching option requires initial investment because of the changes in technology, and / or the building of new facilities. As a result, this strategy is particularly attractive for dealing with power plants more than 30 years old, which may already need renovation and modernization.

The differences in using cleaner fuels can be seen in California. Coal-fired power plants in California are cogeneration plants using mainly natural gas. These facilities are significantly cleaner than other solely coal-fired facilities throughout the West.

Current Control Technologies for Coal-fired Power Plants

Review of current emission reduction practices at coal-fired power plants provides a starting point for discussing strategies that might lead to additional co-benefits for other pollutants as well as mercury. Information Collection Request (ICR) data collection effort, which involved EPA, The National Energy Technology Laboratory (NETL), Electric Power Research Institute (EPRI) and a variety of other groups as well as the utilities themselves, provides valuable and comprehensive information on mercury emissions from utilities all over the U.S. In Phase I of the ICR, information on fuels and controls was collected for all coal-fired

utilities in the U.S. In Phase II, coal data was collected and analyzed for 1140 units and in Phase III mercury measurements, before and after controls, were made at around 85 selected utilities using the modified Ontario Hydro (OH) Method for total and speciated mercury (EPA—ICR, EPA 2002).

The ICR responses indicate that a variety of emission control technologies are employed to meet requirements for sulfur dioxide (SO₂), nitrogen oxides (NO_x), and particulate matter (PM). Most utilities control NO_x by combustion modification techniques and SO₂ by the use of compliance coal. For post-combustion controls, 77.4% have PM control only, 18.6% have both PM and SO₂ controls, 2.5% have PM and NO_x controls, and 1.3% have post combustion control devices for all three pollutants.

Specific types of post combustion control devices include the following:

PM: electrostatic precipitators (ESPs), fabric filters (FFs) that are also called baghouses, and particulate scrubbers (PS). ESPs and FFs may be classified as either cold-side (CS) or hot-side (HS) depending on whether it is installed upstream or downstream of where the flue gas is heated.

SO₂: wet flue gas desulphurization (FGD) scrubbers, semi-dry scrubbers, and dry injection. Wet FGD scrubbers dissolve soluble gases in a solution and a PM control device (i.e., PS, CS-ESP, HS-ESP or FF) is always located upstream of the scrubber. Semi-dry scrubbers include spray dryer absorption (SDA). Dry injection involves injecting dry powdered lime or other suitable sorbent directly into the flue gas. A PM control device (i.e., ESP or FF) is always installed downstream of a semi-dry scrubber or dry injection point to remove the sorbent from the flue gas.

NO_x: selective non-catalytic reduction (SNCR) and selective catalytic reduction (SCR) processes. With both of these methods, a reducing agent such as ammonia or urea is injected into the duct to reduce NO_x to N₂. SCR operates at lower

temperatures than SNCR and is more effective at reducing NOX but it is more expensive.

The ICR results survey shows that for PM control, ESPs are found on 84% of units and FFs on 14%. Post combustion SO₂ controls are less common with FGD systems being used on 15.1% of the units and SDA being used on 4.6% of units surveyed. While the application of post-combustion NO_x controls is becoming more prevalent, only 3.8% of units used either SNCR SCR systems in 1999.

Mercury Control Factors

Analysis of the ICR data indicated that the air pollution control technologies now used on coal-fired utility boilers exhibit levels of mercury control that range from 0% to 98%. This range reflects the difference in composition of the coal (i.e., amount of chlorine and fly ash which contains calcium, iron and carbon compounds), the resulting forms of the mercury (i.e., relative amounts of elemental vapor, reactive vapor or particulate) produced during combustion, and the control technology.

When mercury-containing materials are burned, a series of reactions take place. Some of these reactions reduce the mercury back to its elemental mercury state as a vapor. Other reactions, particularly if chlorides or sulfides are present, will produce divalent (i.e., ionic) reactive gaseous mercury compounds, which are water-soluble and/or particulate mercury, which may combine/agglomerate with other ash particles in the gas stream. Lower temperatures favor condensation from gas to particle phase. There is also experimental evidence that oxidation of elemental mercury is promoted by constituents of fly ash (i.e., calcium, carbon and iron compounds). The presence of acid gases (e.g., hydrochloric, sulfuric and nitric) in the flue gas has also been shown to cause oxidation in the presence of fly ash. (e.g., Senior, 2001)

The ICR analysis indicate that bituminous coals emit relatively more oxidized (ionic) mercury than do subbituminous and lignite coals and subbituminous and lignite coals emit

relatively more elemental mercury than does bituminous coal. All three coals emit less mercury in the particulate form than in the other two gaseous forms.

The properties of emitted mercury determine how effective post combustion control technologies, designed for reducing other pollutants, are in reducing the mercury emissions. Particulate mercury can be captured in controls designed for reducing particulate (PM) emissions. The oxidized forms of mercury generally are soluble, with the solubility varying depending on the specific chemical form. These soluble mercury compounds can be trapped in wet scrubbing devices designed for controlling SO₂. Elemental mercury is not soluble so it cannot be captured in wet scrubbers. The dry technique for capturing SO₂ is also applicable to mercury. Both elemental and reactive mercury gas can be adsorbed onto porous solids such as fly ash, powdered activated carbon (PAC) or calcium based acid gas sorbents for subsequent collection in a PM control device. The reactive form is easier to adsorb than the elemental form of mercury. Selective catalytic reduction processes designed to reduce NO_x by converting NO_x to N₂ (basic air molecule) also seem to be effective at enhancing the oxidation of mercury to forms that are more readily captured.

Control Techniques and Mercury Removal Efficiencies

The air pollution control technologies now used on pulverized-coal-fired utility boilers exhibit average levels of mercury control that range from 0 – 98%. The amount of mercury captured by a given control technology is better for bituminous coal than for either subbituminous coal or lignite, as expected given the higher relative amounts of fly ash carbon content and of the more easily captured oxidized forms of mercury associated with combustion of bituminous coal. The best levels of control are generally obtained by systems that use FFs for PM control. Added SO₂ wet scrubbing FGD or dry adsorption SDA controls enhance removal of mercury for bituminous and, to a lesser extent, for subbituminous.

As implied by the ICR results, it seems that mercury emission reductions are being achieved now as a result of secondary effectiveness of SO₂, NO_x and PM controls, not dedicated mercury controls. In particular, significant co-benefits for mercury can be obtained

from use of FGD aimed at SO₂ control, SCR/SNCR for NO_x control, and ESP and FF for particulate control. Application of these controls for locations using bituminous coal would be particularly effective.

Current levels of mercury control can be increased by application of retrofit technologies or methods designed to increase capture. For example, tests have shown that mercury capture in PM control devices generally increases as the carbon content of fly ash increases. Increased use of combustion modification techniques that increase ash carbon content will generally increase the amount and capture of mercury in its particulate form. The EPA ICR data also indicate that chemistry associated with the SCR systems may be enhancing the oxidation of mercury and, as a result, increasing capture efficiency.

Several potential retrofit technologies are considered to be feasible and cost-effective ways to enhance mercury capture using current in-place technologies.

ESP and FF Systems:

- inject a sorbent upstream of the ESP or FF,
- inject a sorbent between the ESP and a pulsejet FF retrofitted downstream of ESP, and
- install a semi-dry circulating fluidized bed (CFA) adsorber upstream of existing ESP.

SDA Systems:

- modify with sorbents that more effectively capture mercury, and
- Use CFA with wet lime reagents instead of spray dryers using calcium-based sorbents.

Wet FDG Systems:

- inject oxidizing agents to enhance the oxidation of elemental mercury, and
- install fixed oxidizing catalysts upstream of scrubber to promote oxidation.

Research continues on ways to improve mercury capture by the various existing conventional emission control devices, sorbent injection, and the development of novel techniques. Powdered Activated Carbon (PAC) injection is considered a potential control technology for mercury emitted from electric utilities, since a form of this technology has been successfully demonstrated for about 10 years on medical waste incinerators, municipal waste combustors (MWC) and hazardous waste combustion systems. Activated carbon is best used in

a dry system followed by a fabric filter. The activated carbon is injected before the fabric filter and, if necessary, a water mist used to cool the flue gas. In cases where a spray dryer fabric filter system is used, then the gas cooling occurs in the spray dryer and no cooling mist is necessary.

The addition of sulfur compounds also has been found to enhance mercury removal. In tests performed with wet scrubbing systems, the addition of sodium sulfide (Na_2S) has been shown to remove about 80% of the mercury in a gas stream. The sodium sulfide reacts with various forms of the mercury to form mercuric sulfide, an extremely insoluble compound. The mercuric sulfide is separated out from the scrubber liquor and removed. As with the use of activated carbon, the effectiveness of sodium sulfide is proportional to the mass ratio of the sodium sulfide to the mercury in the gas stream. Work with proprietary adsorbents, sponsored by the DOE, has given similar results to that achieved through the use of activated carbon with or without sulfur enhancement.

Recent discussions (EPA, 2001d) of feasible levels of near- and long- term control suggest that significant improvement, particularly for subbituminous coal could be achieved in the near term (i.e., 2007-2008). Longer-term strategies could bring efficiencies up to 85% to 98%, depending on coal and control technologies.

Ongoing evaluation of retrofit technologies at plants where co-control are being practiced will lead to more thorough characterization of the performance and costs of mercury control. Similarly, continued evaluations of new system variations, such as the addition of PAC injection to existing systems, will help establish comparative costs and effectiveness at reducing mercury along with other pollutants.

One potential adverse side effect of increased control of mercury emissions from coal-fired power plants is the possible change in the amount and composition of coal combustion residues (CCRs). Such changes may increase the potential for release of mercury to the environment from either land filling or use of these CCRs. Mercury volatilization or leaching is possible during any phase of the CCR life cycle from production to usage to disposal. Available CCR data show a range of values for mercury concentration based on varying mercury contents

in the input coal and mercury capture rates for control devices. Mercury volatilization of CCRs in landfills is expected to be low due to the low temperatures involved. However, due to the potential increase in mercury content of residues, additional study on the real potential of this impact is needed.

Western Utilities

During the ICR process, all of the major utilities in the west were required to report information on their current operations. A number of facilities also were included in the detailed sampling phase of the ICR that provided data on mercury capture efficiencies for current coal type and control configurations. The available information, as reported during the ICR, reflects activities as of 1999. Examination of individual western plant operations and the estimated, expected mercury control efficiencies based on the ICR information and analysis, provides an indication of current mercury emission levels, the type of mercury being emitted and where additional retrofits might be beneficial.

As shown in Table 2, western utilities typically use bituminous or subbituminous coal and have a variety of controls in place for PM, SO₂ and NO_x. Other factors to note are that western coals are somewhat different from other U.S. coals in their chlorine and fly ash content (CoalAge, 2002). The higher chlorine content in particular may give rise to enhanced oxidation of elemental mercury for these western coals. For this overview, the efficiencies of different coal type and control combinations are determined directly from the ICR study results.

Table 2. Western Facility Emissions, Current Controls, and Suggested Mercury Retrofits

Plant	Boiler	(Tons)	Coal			Controls			Hg Avg	Emitted Hg %			Retrofit
Name and State	Num	Hg 1999	Lig.	Sub.	Bit.	NOX.	SO2.	PM.	Removed	Part.	Oxid.	Elem.	Suggestions**
Apache Station	AZ	2	0.025		x	OFA	FGD	ESP-HS	29%	1%	4%	94%	Oxidizing Agent
		3	0.029		x	OFA	FGD	ESP-HS	29%	1%	4%	94%	Oxidizing Agent
Cholia	AZ	3	0.03		x	None	None	ESP-HS	6%	0%	13%	87%	Sorbent/New FF
		2	0.034		x	None	None	PS	9%	1%	5%	93%	Sorbent
		1	0.006		x	None	FGD	PS	[0%]	1%	5%	93%	Oxidizing Agent
		4	0.046		x	None	FGD	ESP-HS	29%	1%	4%	94%	Oxidizing Agent
Coronado	AZ	U1B	0.063		x	OFA	FGD	ESP-HS	29%	1%	4%	94%	Oxidizing Agent
		U2B	0.05		x	OFA	FGD	ESP-HS	29%	1%	4%	94%	Oxidizing Agent
Irvington	AZ	4	0.001		x	LNB	CC	FF	72%	1%	83%	16%	Sorbent
Navajo	AZ	3	0.043			None	FGD	ESP-HS	49%	1%	21%	79%	Oxidizing Agent
		1	0.04		x	None	FGD	ESP-HS	49%	1%	21%	79%	Oxidizing Agent
		2	0.054		x	None	FGD	ESP-HS	49%	1%	21%	79%	Oxidizing Agent
Springerville	AZ	1	0.076		x	LNB	SDA	FF	24%	1%	4%	95%	Sorbent
		2	0.07		x	LNB	SDA	FF	24%	1%	4%	95%	Sorbent
Arapahoe	CO	1	0.007		x	None	SDA/CC	ESP-CS	35%	0%	4%	96%	Sorbent
		2	0.001		x	None	CC	ESP-CS	3%	0%	31%	69%	Sorbent-CFA
		3	0.002		x	None	CC	FF	72%	1%	83%	16%	Sorbent
		4	0.014		x	LNB	SDA/CC	FF	24%	1%	4%	95%	Sorbent
.....	CO	2	0.001		x	LNB	CC	FF	90%	4%	63%	33%	Sorbent
Cherokee	CO	1	0.0001		x	LNB	SDA	FF	98%	9%	29%	62%	Sorbent
		2	0.0009		x	OFA	CC	FF	90%	4%	63%	33%	Sorbent
		3	0.0013		x	LNB	CC	FF	90%	4%	63%	33%	Sorbent
		4	0.0003		x	LNB	SDA	FF	98%	9%	29%	62%	Sorbent
Comanche	CO	1	0.019		x	None	CC	FF	72%	1%	83%	16%	Sorbent
		2	0.019		x	OFA	CC	FF	72%	1%	83%	16%	Sorbent
Craig	CO	C3	0.016		x	LNB	FGD	ESP-HS	29%	1%	4%	95%	Oxidizing Agent
		C1	0.027		x	LNB	SDA	FF	24%	1%	4%	94%	Sorbent
		C2	0.029		x	LNB	FGD	ESP-HS	29%	1%	4%	95%	Oxidizing Agent
Hayden	CO	H1	0.0002		x	LNB	SDA/CC	FF	98%	9%	29%	62%	Sorbent
		H2	0.0035		x	LNB	SDA/CC	FF	98%	9%	29%	62%	Sorbent
Martin Drake	CO	5	0.0007		x	LNB	CC	FF	72%	1%	83%	16%	Sorbent
		6	0.0014		x	LNB	CC	FF	72%	1%	83%	16%	Sorbent
		7	0.002		x	LNB	CC	FF	72%	1%	83%	16%	Sorbent
Nucla	CO	1	0.01		x	FBC	FBC	FF	[92%]	2%	39%	59%	Sorbent
Pawnee	CO	1	0.049		x	LNB	CC	FF	72%	1%	83%	16%	Sorbent
Rawhide	CO	101	0.031		x	OFA	SDA	FF	24%	1%	4%	95%	Sorbent
Ray O. Nixon	CO	1	0.003		x	LNB	CC	FF	72%	1%	83%	16%	Sorbent
Valmont	CO	5	0.001		x	LNB	CC	FF	90%	4%	63%	33%	Sorbent
Colstrip	MT	3	0.131		x	LNB	None	PS	9%	1%	5%	93%	Sorbent/NewFF
		1	0.05		x	OFA	None	PS	9%	1%	5%	93%	Sorbent/NewFF
		2	0.054		x	OFA	None	PS	9%	1%	5%	93%	Sorbent/NewFF
		4	0.16		x	LNB	None	PS	9%	1%	5%	93%	Sorbent/NewFF
J.E. Corette	MT	2	0.015		x	OFA	None	ESP-CS	3%	0%	31%	69%	Sorbent-CFA
Lewis & Clark	MT	B1	0.009		x	LNB	None	PS	[33%]	0%	3%	97%	Sorbent/NewFF
Escalante	NM	1	0.043		x	OFA	FGD	FF	[72%]	1%	83%	16%	Oxidizing Agent
Four Corners	NM	1	0.047		x	LNB	FGD	PS	[0%]	1%	5%	93%	Oxidizing Agent
		4	0.164		x	LNB	FGD	FF	[72%]	1%	83%	16%	Oxidizing Agent
		2	0.045		x	LNB	FGD	PS	[0%]	1%	5%	93%	Oxidizing Agent
		3	0.063		x	LNB	FGD	PS	[0%]	1%	5%	93%	Oxidizing Agent
		5	0.158		x	LNB	FGD	FF	[72%]	1%	83%	16%	Oxidizing Agent
San Juan	NM	1	0.094		x	LNB	FGD	ESP-HS	29%	1%	4%	94%	Oxidizing Agent
		2	0.089		x	None	FGD	ESP-HS	29%	1%	4%	94%	Oxidizing Agent
		3	0.156		x	LNB	FGD	ESP-HS	29%	1%	4%	94%	Oxidizing Agent
		4	0.133		x	LNB	FGD	ESP-HS	29%	1%	4%	94%	Oxidizing Agent
Mohave	NV	1	0.054		x	None	None	ESP-CS	3%	0%	31%	69%	Sorbent-CFA
		2	0.05		x	None	None	ESP-CS	3%	0%	31%	69%	Sorbent-CFA
North Valmy	NV	1	0.003		x	LNB	CC	FF	90%	4%	63%	33%	Sorbent
		2	0.0004		x	LNB	SDA	FF	98%	9%	29%	62%	Sorbent
Reid Gardner	NV	1	0.012		x	LNB	FGD	PS	12%	2%	20%	79%	Oxidizing Agent
		4	0.001		x	LNB	FGD	FF	97%	6%	33%	61%	Oxidizing Agent
		2	0.012		x	LNB	FGD	PS	12%	2%	20%	79%	Oxidizing Agent
		3	0.017		x	LNB	FGD	PS	12%	2%	20%	79%	Oxidizing Agent

Table 2 (Continued). Western Facility Emissions, Current Controls, and Suggested Mercury Retrofits

Plant	Boiler	(Tons)	Coal			Controls			Hg	Emitted Hg %			Retrofit
Name and State	Num	Hg 1999	Lig.	Sub.	Bit.	NOX.	SO2.	PM.	Avg Removed	Part.	Oxid.	Elem.	Suggestions**
Boardman	OR	1SG	0.084		x	LNB	none	ESP-CS	3%	0%	31%	69%	Sorbent/NewFF
Bonanza	UT	"1-1"	0.002		x	LNB	FGD	FF	98%	6%	33%	61%	Oxidizing Agent
Carbon	UT	1	0.008		x	None	None	ESP-CS	36%	6%	68%	26%	Sorbent-CFA
		2	0.01		x	None	None	ESP-CS	36%	6%	68%	26%	Sorbent-CFA
Hunter	UT	1	0.016		x	OFA	FGD	ESP-CS	75%	0%	8%	92%	Oxidizing Agent
		3	0.002		x	LNB	FGD	FF	98%	6%	33%	61%	Oxidizing Agent
		2	0.019		x	OFA	FGD	ESP-CS	75%	0%	8%	92%	Oxidizing Agent
Huntington	UT	1	0.016		x	None	FGD	ESP-CS	75%	0%	8%	92%	Oxidizing Agent
		2	0.051		x	None	None	ESP-CS	36%	0%	67%	33%	Sorbent-CFA
Intermountain	UT	2SGA	0.002		x	LNB	FGD	FF	98%	6%	33%	61%	Oxidizing Agent
		1SGA	0.002		x	LNB	FGD	FF	98%	6%	33%	61%	Oxidizing Agent
Centralia	WA	BW21	0.122	x		None	None	ESP-CS	3%	0%	31%	69%	Sorbent-CFA
		BW22	0.118	x		None	None	ESP-CS	3%	0%	31%	69%	Sorbent-CFA
Dave Johnston	WY	BW41	0.021	x		None	None	ESP-CS	3%	0%	31%	69%	Sorbent-CFA
		BW42	0.022	x		None	None	ESP-CS	3%	0%	31%	69%	Sorbent-CFA
		BW43	0.036	x		None	None	ESP-CS	3%	0%	31%	69%	Sorbent-CFA
		BW44	0.061	x		None	FGD	PS	[0%]	1%	5%	93%	Oxidizing Agent
Jim Bridger	WY	BW74	0.066	x		LNB	FGD	ESP-CS	29%	0%	3%	97%	Oxidizing Agent
		BW71	0.074	x		LNB	FGD	ESP-CS	29%	0%	3%	97%	Oxidizing Agent
		BW72	0.074	x		LNB	FGD	ESP-CS	29%	0%	3%	97%	Oxidizing Agent
		BW73	0.066	x		LNB	FGD	ESP-CS	29%	0%	3%	97%	Oxidizing Agent
Laramie River	WY	3	0.072	x		LNB	SDA	ESP-CS	0%	0%	4%	96%	Sorbent
		1	0.076	x		LNB	FGD	ESP-CS	16%	0%	3%	97%	Oxidizing Agent
		2	0.077	x		LNB	FGD	ESP-CS	16%	0%	3%	97%	Oxidizing Agent
Naughton	WY	1	0.022	x		None	None	ESP-CS	3%	0%	31%	69%	Sorbent-CFA
		2	0.028	x		None	None	ESP-CS	3%	0%	31%	69%	Sorbent-CFA
		3	0.031	x		None	FGD	ESP-CS	16%	0%	3%	97%	Oxidizing Agent
Wyodak	WY	BW91	0.083		x	LNB	SDA	ESP-CS	29%	0%	4%	96%	Sorbent

Facility Controls & Mercury(Hg) Data based on Information Collection Request (ICR) - 1999.

Hg total emissions from all units within a facility. Estimates of Hg removal and species emitted based on analysis of individual units.

Western plants are listed. Plant totals for 1999. Information listed for all coal-fired units within a facility.

Controls: NOX. Low NOX Burner (LNB) and Over-fire air (OFA) are NOX control measures in the combustion process

SCR/SNCR are post combustion NOX controls using chemical reactions with/without a catalyst

Controls: SO2. Fluidized Bed combustion (FBD) uses limestone to reduce SO2 during combustion process.

Flue gas desulfurization (FGD) wet scrubbing and Dry lime adsorber (SDA) are post combustion controls

Use of compliance coal (CC)

Controls: Particulate Matter (PM). Fabric Filters (FF) or baghouses collect PM on filters.

Electrostatic Precipitators (ESP, installed upstream-hot side (HS) or downstream cold-side (CS) of air preheater.

Particle wet scrubbers (PMScrub), Mechanical or Cyclone (Mach or Cyc)

Average mercury (Hg) removed as a function of coal type and controls.

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Red indicates the plant units that were specifically measured as part of the ICR study.

Blue indicates that the plant units that were not sampled.

Emitted mercury speciation is based on analysis and estimated average results for sampled units with the same coal type-control configuration.

****Suggested retrofits based on examination of ICR analysis. Assumes that the same coal type-control configurations remain.**

Sorbent/New FF: Inject sorbent between ESP and pulsejet FF retrofitted down stream of the ESP (could be used for HS or CS)

Sorbent-CFA: Install CFA upstream of ESP-CS in conjunction with sorbent injection or just use sorbent without CFA.

Sorbent: Inject sorbent upstream of FF or ESP-CS

Sorbent: When SDA is also present, inject sorbent for Hg capture into SDA system

Oxidizing Agent: Inject appropriate oxidizing agent into the FGD or install fixed oxidizing catalysts upstream of scrubber.

EPA/ORD and DOE/NETL are studying various oxidizing agents and sorbents to determine effectiveness.

Activated carbon is considered to be one promising sorbent.

A number of the facilities are already capturing over half of the emitted mercury. This is mainly the result of using bituminous coal and/or having fabric filter (FF) in place for PM control. Some facilities have SO₂ controls in addition to FF that generally enhances mercury capture efficiency for both bituminous and subbituminous coal. Based on the available measurements used to estimate relative amounts of different mercury species being emitted after the controls for different coal and control combinations, elemental mercury generally is the dominant form of mercury emitted post control.

When considering retrofits to enhance mercury control, several options might be considered. In some cases, improvement can be attained with the current controls and coal type in place. These potential modifications include use of effective sorbents to enhance mercury adsorption to particles which are then captured by the PM control devices; use of oxidizing agents to promote further conversion of elemental mercury to more soluble oxidized forms of mercury which can be more readily captured in wet scrubbers in place for SO₂ capture; or the addition of more effective supplemental PM capture devices. Switching from subbituminous or lignite coal to bituminous coal would increase mercury capture for most configurations. Addition of control devices to enhance SO₂ and NO_x control also would enhance mercury control for most cases. The relative effectiveness, costs and other considerations of any of these options should be carefully assessed for each individual unit to determine what is most feasible and effective for the particular facility.

Control Costs

Many utilities, and in particular many western utilities, already are equipped with control technologies which are effective in reducing mercury. Many others could achieve further reductions through retrofit technology strategies that enhance mercury reduction through addition of current controls which have demonstrated effectiveness, use of improved pollutant sorption techniques, and implementation of processes that enhance oxidation of elemental mercury to oxidized forms which are more readily captured. Reduction of all forms of mercury is important since even the less reactive elemental form which, when emitted, is likely to travel

long distances, will eventually be deposited and contribute to the overall global potential for adverse impacts related to mercury.

When considering retrofits to enhance mercury control, several options might be considered. In some cases, improvement can be attained with the current controls and coal type in place. These potential modifications include use of effective sorbents to enhance mercury adsorption to particles which are then captured by the PM control devices; use of oxidizing agents to promote further conversion of elemental mercury to more soluble oxidized forms of mercury which can be more readily captured in wet scrubbers in place for SO₂ capture; or the addition of more effective supplemental PM capture devices. Switching from subbituminous or lignite coal to bituminous coal would increase mercury capture for most configurations. Addition of control devices to enhance SO₂ and NO_x control also would enhance mercury control for most cases. The relative effectiveness, costs and other considerations of any of these options should be carefully assessed for each individual unit to determine what is most feasible and effective for the particular facility.

Some preliminary studies of cost comparisons are beginning to provide some insight into costs of retrofits for different control configurations. For example, EPA (2002b) presented annualized costs of mercury controls using powdered activated carbon (PAC) injection to enhance mercury capture in existing control devices. This study was based on recent pilot-scale evaluations with commercially available adsorbents. The control costs are lowest for fabric filter (FF) and highest for hot-side electrostatic precipitators (ESP-HS). Costs are also lower for systems that include PM controls with sulfur controls, which the case for facilities using higher sulfur coals. Finally, retrofits for bituminous coal are less expensive than those for subbituminous coal. The second column of costs illustrates projected reductions that would occur if a composite lime and PAC sorbent is used. It is projected that this would result in a 40% reduction in sorbent costs. It is projected that better sorbents and technologies now being developed will reduce the costs of Hg controls beyond current estimates.

The extra costs of using SCR for NO_x control to further enhance mercury control appear to be small if the SCR is accompanied with PM control and FGD for SO₂. The ICR analysis

indicate that for a flue gas which starts with 70% oxidized mercury, SCR augments oxidation by 35%, leading to a total of 94.5% of total mercury being oxidized. This mercury is then found to be completely removed by the other controls. The cost of this mercury removal is estimated at 0.006 mill/kWh, which is simply the cost of monitoring the mercury emissions.

Within the next two to three years the evaluation of retrofit technologies at plants where co-control is being practiced will lead to more thorough characterization of the performance and costs of Hg control. Future cost studies will focus on the development of performance and cost information needed to refine cost estimates for sorbent injection based controls, will develop cost estimates of wet scrubbing systems that employ methods for oxidizing elemental mercury, and will determine the costs of various multipollutant control options.

In addition to these analyses, other EPA studies have examined co-benefits of strategies dealing with mercury, SO₂, NO_x and CO₂. The studies show that having advance knowledge of potential requirements for all pollutants (Hg, SO₂, NO_x, and CO₂) currently under consideration for legislation could lead firms to follow significantly different compliance strategies at individual plants, compared with compliance choices made when the pollutants are addressed one-by-one. Modeling results suggest that firms complying with a potential SO₂ reduction requirement would choose to install substantially fewer sulfur scrubbers if they had advance knowledge that a specific carbon reduction will also be required. One example indicates that a 50% SO₂ reduction undertaken together with a 9% domestic carbon reduction is estimated to cost \$450 million less per year than the total cost of the two strategies examined separately. This integrated strategy would have more modest impacts on fuel patterns than previously predicted. A recent report released by the Department of Energy's Information Administration also notes that a four-pollutant strategy would be more cost effective than a three-pollutant approach, which would omit CO₂.

Linking the success of SO₂, NO_x, PM and Hg co-pollutant approaches with the considerations of the SO₂, NO_x, Hg and CO₂ programs, the potential for addressing the integrated mix of five pollutants becomes an attractive alternative.

Other strategies building on gasification technology are being explored. A recent Department of Energy report (Department of Energy, 2002) outlines costs to control mercury from coal using gasification technology and carbon beds. They conclude that 90-95% removal is achievable with one bed and 99%, with two beds in sequence. The costs of this are an order of magnitude lower than mercury control from pulverized coal boilers. The report also concludes that the 90-95% removal can be achieved with an increase of less than 1% in the cost of generating electricity and 99% removal would involve an increase of about 1.5%. In addition, another report (Department of Energy, 2002) explores the relative costs of developing a new integrated gasification combined cycle (IGCC) plant versus a new conventional pulverized coal plant and found that the IGCC option is less costly.

Mercury Control Options. Coal-fired power plants are the major sources of mercury in the western U.S. When developing TMDLs for contaminated waters in the West, reductions in emissions from these sources may be deemed necessary. Reductions can be achieved through pollution prevention, such as fuel cleaning and fuel switching, and through technological control of emissions. Many western utilities already are equipped with control technologies that are effective in reducing mercury. Many others could achieve further reductions through retrofit technology strategies. Of particular merit are technologies that enhance mercury reduction through addition of current controls, which have demonstrated effectiveness. Most promising strategies are use of improved pollutant sorption techniques, and implementation of processes that enhance oxidation of elemental mercury to oxidized forms, which are more readily captured. Use of this information on control possibilities in the development of strategies to protect contaminated waters in the West will need to be discussed during the development of the workshop exit strategy.

Conclusions

Mercury continues to represent a threat to sensitive populations in the U.S. and around the world. Establishing detailed quantitative relationships between specific sources and adverse impacts is challenging since emitted mercury can be deposited very close to a source or can travel around the world. As a result, many areas like the Western U.S. are both affected by mercury from nearby and distant sources and are themselves sources of mercury that can cause adverse impacts locally as well as regionally and globally.

The assessment challenge is being addressed by the growing combined forces of air and water analysts. Characterization of air deposition to individual contaminated water bodies from nearby and distant air emission sources is important for developing long term, effective emission reduction strategies. These assessments are being done using a variety of modeling approaches. For areas impacted by a variety of sources, the more complex modeling tools may be the best, if not only, sound approach.

For many areas throughout the U.S. in general and the West in particular, coal-fired utility boilers are major contributors to contamination and are the remaining major source of unregulated mercury emissions. Reductions can be achieved through pollution prevention, such as fuel cleaning and fuel switching, and through technological control of emissions. All forms of mercury need to be reduced since even the less reactive elemental form which, when emitted, is likely to travel long distances, will eventually be deposited and contribute to the overall global adverse impacts related to mercury.

In terms of addressing the technical assessment and policy challenges that remain, continued close collaboration of air and water analysts will be needed. Given the global nature of mercury source-receptor relationships, international collaboration also will be needed to insure that necessary long-term reductions in harmful levels of mercury will be possible in the U.S. and around the world.

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Workshop Charge to the Participants

The workshop participants helped shape an exit strategy that will provide guidance for future treatment of mercury air deposition in protection of water bodies at risk. These discussions also directly assist Colorado in its current TMDL development.

Summary

The overarching question facing the workshop and the mercury assessment and policy communities concerns determining and dealing with mercury air emission sources that contaminate specific water bodies. To begin to better address these science and policy challenges, the workshop exit strategy explored how to:

- improve understanding of mercury in the West
- conduct assessments to identify important sources and reductions needed
- complete next phase of Colorado's TMDL and address other western TMDLs
- determine how mercury air policies can best protect Western water bodies

The following topics formed the framework for exit strategy discussions.

Global Cycle. General strategies for taking multiple uncertainties in the source to impact relationships into account

Emissions. Estimates of contributions from natural, re-entrained and distant sources, estimates of sources special to western states including forest fires and mines, and use of available national inventories for Western studies

Transport and Transformation. Reasonable ways to approximate important atmospheric transport and transformation processes that determine mercury source-receptor relationship

Deposition. Use of available deposition data including monitoring data, snowpack information and ice core results to establish an indication of deposition rates particularly at contaminated sites

Measurements. Availability of more detailed measurement techniques for enhancing studies of air deposition to threatened waters in the West

Health Impacts. Pollution reduction strategies that take into account connections between mercury and other pollutants that enhance mercury mobility and toxicity and recognized the uncertainties associated with current estimates of risk

Fish Advisories. Use of fish advisories to characterize patterns of mercury impacts throughout the West

Mercury Maps. Steps needed to apply the mercury maps approach in the West

Assessment Approaches and Findings. Approaches that adequately consider multiple, diverse and distributed sources

Assessment Strategies. Opportunities for using comprehensive models and cases where simpler approaches would provide useful screening analyses for Western studies

TMDL Process. Necessary steps for determining the relative importance of different air deposition vs. other pathways

Colorado TMDL. Advice for Phase 2 data collection and analysis

Western TMDLs. Listing of ongoing studies, resources, contacts and challenges in the western states and opportunities for combining resources and analyses

Regional Approaches. Western regional approaches that could help to better achieve water protection goals throughout the West

Regulations and Strategies. Level of mercury emissions reductions that may be needed to protect western waters, steps to achieve these reductions, and approach to dealing with additional emission reductions that may be needed outside of vicinities of threatened waters and perhaps, even outside of the US.

Mercury Control Options. Use of information on control possibilities in the development of strategies to protect contaminated waters in the West

At the end of the workshop, the participants will be asked to discuss the following questions in small groups. The participants also will be asked to complete the follow-up information forms individually. This information will help in the development of a workshop strategy and post-workshop review that will be of value to all of the participants.

Exit Strategy Questions

Understanding Mercury

Global Cycle

What are the key questions remaining regarding the cycling (i.e., transport, chemistry, deposition, impacts) of mercury in the western US and how can we best address them?

Emission Inventories

What level of confidence do we have that the major sources or source categories within the United States and within the Western US have been identified and do we need a comprehensive Western regional emission inventory?

Deposition

How are disparate data sets used best in determining overall mercury deposition and what should be high priority areas for mercury deposition research?

Assessments

Tools. What tools and assessment approaches do you see as most promising in improving the understanding of mercury deposition in the West?

Models. What are the next challenges and opportunities for improving mercury modeling in the West?

Total Maximum Daily Load

Western TMDLs. Besides money, what do western states need most in addressing mercury TMDLs?

Colorado TMDLs. What specific suggestions do you have for improving Colorado's TMDL approach?

Regional Approaches. How best can the Western states work together to address mercury issues that are regional in nature?

Post-workshop Information Request

Please identify current studies (and their contacts) of western U.S. mercury deposition efforts that were not highlighted at this conference.

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What are the most significant barriers in understanding mercury deposition in your respective state, province, city, department, etc. (besides money)?

What type of information on mercury would be most helpful for your job?

What recommendations do you have for next steps in addressing mercury reductions and reducing human health risks in the West?

Is your agency specifically addressing mercury reduction issues and, if so, how?

Do you support a regional approach for TMDL development and eventual control strategy implementation? If so, please identify various options that should be considered on a regional basis. If not, why?

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Exit Strategy Recommendations

The following is a summary of key recommendations that came out of the workshop discussions and presentations. Notes from these discussions as well as written responses from participants are located on the workshop website. Presentations along with abstracts and biographical information on the presenters also can be found on the mercury workshop website <http://www.e3ventures.com/mercury/index.html>. All of these provide more detail on the discussions and presentations.

Understanding Mercury

Global Cycle

Many factors determine the extent to which deposited mercury transforms into toxic methyl mercury. Other chemicals such as sulfate play a role. The form of the mercury that enters the water way is important since chemically reactive mercury is more likely to be further transformed. Land management, such as controlling the water level of reservoirs, influences the concentrations of toxic mercury. These factors need to be taken into account when determining the relative importance of air deposition to formation of methyl mercury and when assessing the contribution of different sources to fish contamination.

Atmospheric processes, which depend on concentrations of other air pollutants, convert different forms of emitted mercury into other chemical forms that may be more readily deposited and then converted to methyl mercury in water. This means that sources of other pollutants in the region also need to be considered in order to characterize how emitted mercury becomes the harmful form in water. In the arid west, dry deposition may be as large as wet deposition, meaning that both must be considered when assessing source-receptor relationships.

Emission Inventories

Many different sources and factors determine emissions in the western states. To help catalogue this information, it would be helpful to have a clearinghouse for air emissions information along with data on factors that determine emissions. For example, it would be useful to have soil mapping to show where fires might be effective in liberating mercury. It also would be helpful to characterize the importance of agricultural waste, coal burns, oil and gas industry and blowing dust as sources of mercury in the west.

Deposition

It is essential to begin to bring together the different data sets associated with western deposition since the monitoring data are so sparse and deals only with wet deposition. Besides beginning to develop a survey of available data, it also will be important to develop guidance on how best to use the different data for analysis of source contributions to contaminated fish.

Assessments

A mechanism for providing detailed information on analysis tools and their applicability to the western mercury concerns is needed for the western states individually and as a whole. Through such a regional process, information would be regularly updated, assessment findings shared and collaboration with other groups involved in air quality modeling and multi-media modeling would be facilitated. As a first step in western assessments, the application of Mercury Maps needs to be investigated. In the longer term, application of regional scale chemical transport and transformation modeling being done for the West through the Western Regional Air Quality Partnership also needs to be considered.

TMDLs

Estimating the relative importance of in-state versus out-of-state air emissions remains a major challenge. More detailed coordination of existing information on sources and fish tissue and their trends will be an important next step for the region. In some states, like Colorado, alternative listing procedures need to be explored in order to protect the fish population from overkill as a result of testing. Characterization of power plant mercury emissions by chemical species for plants where stack measurements are not available can be estimated as a first approximation by looking at mercury speciation from power plants with the same coal use and controls as was presented in this critical review.

An essential step in the assessments of source contributions to contamination is establishing the bioavailability of mercury from all of the key sources to the water body under study. Bioavailability depends on the chemical composition of the mercury being deposited into the water body. Chemical composition from sources, in the air and in the air needs to be established through direct measurement and/or reliable, appropriate modeling.

Given the fact that Colorado waters of concern are reservoirs where the cycles of drying and re-wetting influence mercury levels, land management needs to be considered as part of the mercury reduction strategy. Proportional mercury load reduction strategies using Mercury Maps analysis applied to Colorado or the entire region also should be explored.

Regional Approaches

Data exchange between states that share waters and source contribution is highly recommended. States standards for data collection, analysis and interpretation need to be reconciled. Control/management that involve other factors such as land management and use of alternative energy also need to be part of the regional planning to deal with mercury.

NEXT STEPS

To better address the regional nature of air deposition contributions to toxic mercury in western water ways and fish, continued interaction of the workshop participants, building on the momentum of the workshop, will be an initial outcome of the workshop. The format and objectives of these interactions will be part of a more formal exit strategy to be developed by the workshop organizers.